The Thesis Committee for Sang Ki Lee
Certifies that this is the approved version of the following Thesis

Evaluation of Asphalt Binder and Mixture Properties that Incorporate Reclaimed Asphalt Pavement

APPROVED BY
SUPERVISING COMMITTEE:

____
Amit Bhasin, Supervisor

____
Syeda Rahman

Evaluation of Asphalt Binder and Mixture Properties that Incorporate Reclaimed Asphalt Pavement

by

Sang Ki Lee

Thesis

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2018

Dedication

I would like to dedicate this work to my family.

Acknowledgements

I would like to express my sincere gratitude to Dr. Amit Bhasin, my supervisor, for his guidance and support in conducting this research. The teachings I received from him goes well beyond this research and I believe I'm leaving this program as a better man than the one I entered as. I wish to acknowledge the Texas Department of Transportation (TxDOT) for financially supporting this study. And thanks are due to Syeda Rahman for all her help as the second reviewer.

My extended family, "oh yeah", here at Austin is due for an acknowledgement for the moral support in this endeavor. I would also like to extend my gratitude to Angelo Filonzi for his direct involvement in this research, but more importantly, for his support as a friend. I appreciate all my colleagues, including Ramez Hajj, Tyler Seay, Nazmus Sakib, Rogelio Rodriguez, Rachel Hure, and Alex Giogitti, who helped me along the way of this research.

Last, but not least, I would like to express my sincere gratitude to my family for all their support, love, and motivation. My parents have been unwavering in their love and faith through all that I have done, and words cannot express how grateful I am towards them. Thank you, SangHyuk Lee, for always striving ahead of everyone and aspiring me to do the same.

Abstract

Evaluation of Asphalt Binder and Mixture Properties that Incorporate Reclaimed Asphalt Pavement

Sang Ki Lee, M.S.E

The University of Texas at Austin, 2018

Supervisor: Amit Bhasin

Several private and public agencies are exploring ways in which the use of reclaimed asphalt pavement (RAP) can be increased in the construction of new pavements. However, such an increase must not come at the expense of reduced durability or life cycle cost. The use of RAP is often accompanied by some form of adjustment to the virgin binder that is being used. In Texas, the current practice of incorporating RAP is controlled by a simplified table that lists a substitute binder grade and recycled binder ratio (RBR) when RAP is incorporated in a mix. There are a few shortcomings with this simple approach of specifying a maximum ratio: (1) it does not address the potential difference in the quality of recycled binders from RAP, (2) it may result in the use of substituted binders with little or no polymer (elastomer) and (3) it does not account for the influence of recycling agents. The goal of this study was to evaluate the change in performance of binders and mixtures using different grades of virgin binder and percentages of RAP. Two different Job Mix Formulae (JMF) and corresponding materials were obtained from asphalt plants in the state of Texas. A test matrix was

developed to evaluate binders and mixtures with different ratios of recycled binder to virgin binder and different ratios of RAP to virgin material, respectively. The results from this study show that addition of RAP or recycled binder (from RAP) results in an increase in stiffness and resistance to rutting, which was expected. However, the resistance to cracking showed mixed results. The test results also show that the properties of the recycled binder from RAP can vary significantly with source and have a drastic effect on the properties of the binder and mixture.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 INTRODUCTION AND REVIEW

The demand for safe, durable, and sustainable transportation infrastructure is rising with increasing world population and urban sprawl. In the United States, over 90 percent of highways are constructed using asphalt mixes with majority of the system experiencing clear deterioration in serviceability. In many cases, this deterioration is driven by increasing traffic loads, extended use of roadways beyond their service life, and fiscal constraints on timely maintenance and rehabilitation. This also explains why the American Society of Civil Engineers (ASCE) has evaluated the current system with a grade D (Copeland, 2011). For example, the damage and repair cost due to poor pavement condition totaled at $120.5 billion in 2015 alone. This amount perfectly illustrates the state of condition of our current system. This poor state was not an overnight occurrence. According to some sources, the deterioration and poor condition can, at least partially, be attributed to consistent under-funding by the government, resulting in a $420 billion of backlog just for repairing existing highways and $126 billion for system enhancement (Copeland, 2011). An increase in the demand on the existing pavement infrastructure combined with an emphasis on reduced consumption of non-renewable material resources as well as reduced life-cycle cost has led to innovation and development of several new materials design and pavement construction technologies. One of the most significant of these is to use reclaimed asphalt pavement or RAP to construct and maintain pavements.

There are different asphalt recycling methods including hot in-place, cold in-place, cold mix recycling, and hot mix recycling. Hot mix recycling method is the most widely used (Santucci, 2007). This study will only refer to RAP in the context of using reclaimed asphalt pavement to produce new asphalt mixture for new pavement construction, rehabilitation or maintenance.

Reclaimed asphalt pavement (RAP) is increasingly being used due to the cost savings that can be realized while saving non-renewable material resources. Using RAP reduces the amount of virgin aggregate and virgin asphalt binder consumed during the production of asphalt mixtures while also reducing the reclaimed material from going to the landfill as waste. As public opinion for sustainable future becomes unanimous, the emphasis to develop environment-friendly technologies in transportation infrastructure will become ever present. The use of RAP in asphalt mixture production, if done correctly and responsibly, can provide a solution that addresses both fiscal and environmental constraints imposed on pavement construction technologies. The following paragraphs summarize the current trends in highway agencies across the U.S. in terms of their efforts to incorporate RAP in asphalt mixture production.

In 2007, a survey was performed by North Carolina Department of Transportation (NCDOT) (Copeland, 2011), on behalf of the RAP Expert Task Group (ETG) and sponsored by AASHTO Subcommittee on Materials. The survey revealed that state DOTs intend to increase the amount of RAP used across the United States. Figure 1.1 shows the number of DOTs that used and permitted a specific amount of RAP in the intermediate layers of the pavement structure and Figure 1.2 shows the same number for surface layers. The data clearly show that many construction projects do not use the maximum amount of RAP allowed by their respective state agencies. For example, in Figure 1.1, fifteen state agencies allow 30% and higher in their specification, but only 4 state agencies actually used 30% and higher in their intermediate layer. Figures 1.1 and 1.2 show that there is a difference between the amount of RAP allowed by the state agencies and the amount actually used. Also, the difference between RAP percentage permitted (potential) and actually used (usage) is greater when the allowable RAP percentage is high. This gap illustrates the potential to increase the total amount of RAP used in the U.S.

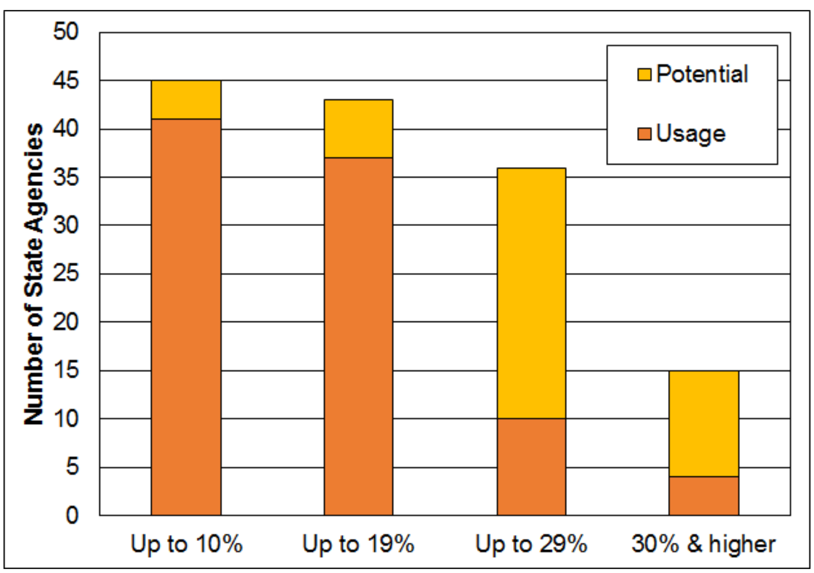

Figure 1.1. Usage and potential of various RAP percentages in the intermediate layer, adopted from Copeland (2011)

A similar survey in 2009 by NCDOT (Copeland, 2011) reported increased RAP

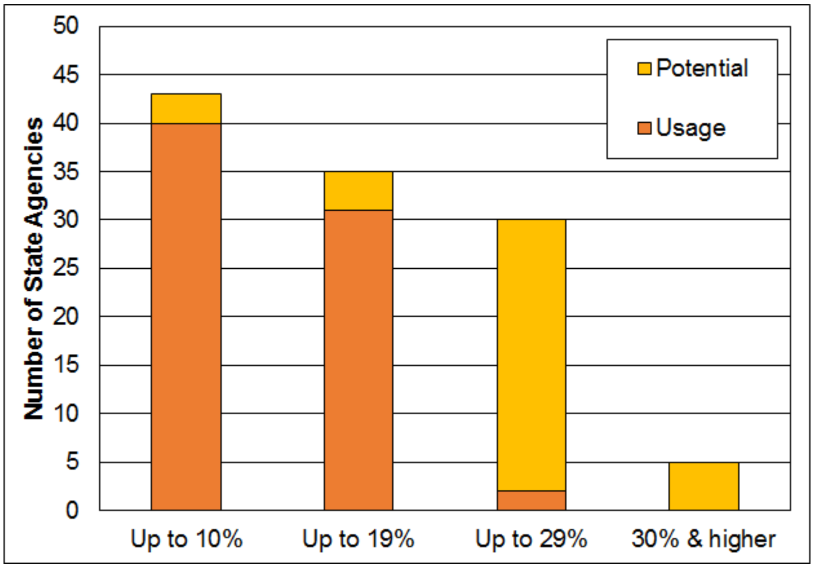

Figure 1.2. Usage and potential of various RAP percentages in the surface layer, adopted from Copeland (2011)

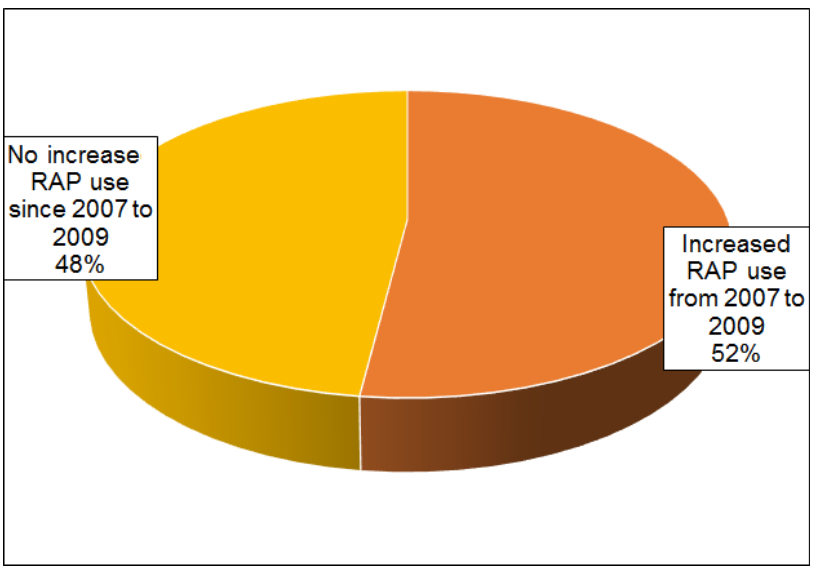

Figure 1.3. Percentage of states with increased RAP use since 2007 to 2009, adopted from Copeland (2011)

usage from 2007 to 2009 (Figure 1.3). Also, more state DOTs were permitting even higher RAP percentages in the mixture to encourage higher use of RAP usage (Figure 1.4).

Similar to the earlier survey, although there was an increase in the maximum allowable percentage of RAP in specifications, the actual percentage used in practice was lower

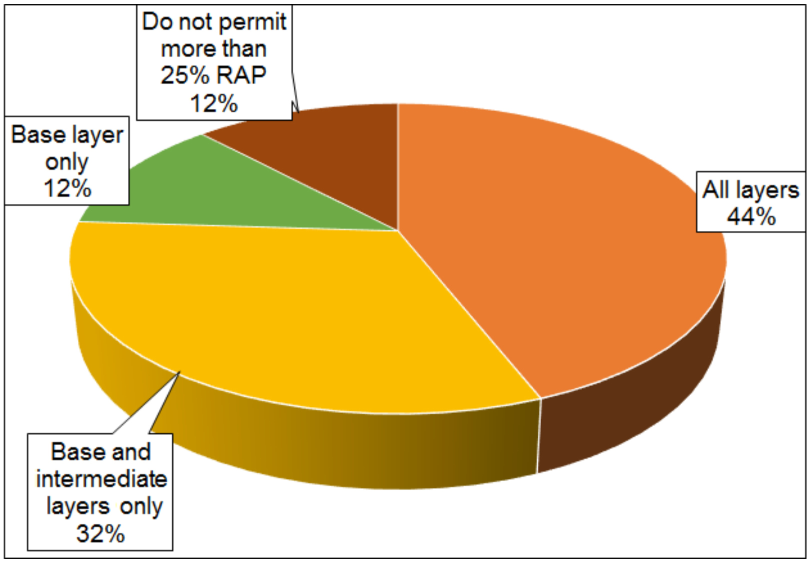

Figure 1.4. Percentage of states that permit more than 25 percent RAP in HMA layers, adopted from Copeland (2011)

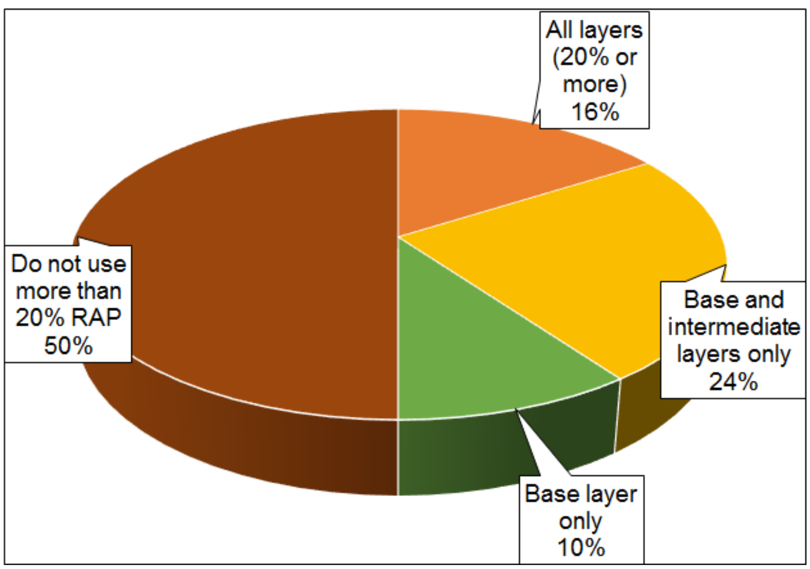

Figure 1.5. Percentage of states that use more than 20 percent RAP in HMA layers, adopted from Copeland (2011)

(Figure 1.5).

In other words, the survey results indicate a clear gap between the desire throughout the U.S. to use higher percentage of RAP and the actual percentage of RAP used on an average in projects. It is speculated that this gap is driven by the reluctance of agency and/or contractors to incorporate higher percentages of RAP on account of the uncertainties associated with the expected performance of the resulting mixture. In order to promote the use of RAP (in any percentage in a mix), the uncertainties associated with the used RAP must be addressed and mixtures incorporating RAP must demonstrate to have equal or improved performance compared to the original mixture design without any recycled material.

Previous studies have demonstrated that asphalt mixtures can be produced to achieve similar or better performance by incorporating RAP. For example, a study performed by Kandhal et al. (1995) on existing pavements with RAP showed promising results. They evaluated pavements that incorporated 10-15% RAP after 1 to 2.5 years of service and recorded no signs of rutting, raveling, or fatigue cracking in any of the test sections. Expanding the study, Kandhal and Foo (1997) studied pavements with 10-40% RAP and recorded no significant difference in the performance of the virgin and recycled pavement sections. However, it is important to note that 1 to 3 years is not sufficient to evaluate the long-term performance of pavement sections that are typically designed for twenty or more years of service life. This is particularly important for fatigue and thermal cracking, which becomes more severe towards the end of the service life of a pavement.

Research carried out by Little and Epps (1980), also reported similar performance between recycled asphalt mixture and virgin asphalt mixture. The study looked at laboratory derived properties, such as, fatigue potential, and the stability of pavement including RAP through indirect tension test and Hveem stability value. The indirect tension tests revealed similar ultimate tensile stress between RAP pavement samples and control samples. The Hveem stability of mixtures incorporating RAP were only slightly lower than successful conventional pavements and within reasonable range. Therefore, the study concluded that mixtures incorporating RAP could be expected to replace conventional asphalt concrete with satisfactory results.

Survey results in the previous section show that highway agencies are not averse to the use of RAP as long as it is done in a responsible way. However, there are a number of uncertainties and challenges that need to be overcome in order to increase the level of confidence and reliability in allowing the use of RAP. For example, inconsistencies in RAP aggregate gradation, RAP fine content, selection of appropriate bulk specific gravity of RAP aggregates, and selection of virgin binder are just a few considerations that need to be better understood and specified. To avoid some of these problems, some DOTs limit the type of RAP allowed for design. For example, some agencies, only allow RAP from specific projects or pavement types to be used in their mixes (West, 2010). In order to facilitate the use of RAP, it would help to overcome these restrictions in lieu of verifying the quality of materials in RAP with routine testing and optimizing the usage of the material. The following section presents a summary of some of the available methods to characterize RAP and optimize the mixture design containing RAP.

1.2 STATE OF PRACTICE

1.2.1 Overview

The most common method to optimize a mix design containing RAP is to use a blending chart. A blending chart assists in the selection of a virgin binder that is appropriate for a mix design that incorporates a certain percentage of RAP (Servas, 1982). In 1997, Kandhal and Foo (1997) developed a procedure for selecting the performance grade (PG) of virgin asphalt binder to be used in asphalt mixtures with RAP. The Federal Highway Administration's (FHWA) RAP ETG also developed interim guidelines for the design of Superpave asphalt mixture containing RAP in the form of a tiered approach to determine the level of testing required during the design of asphalt mixture containing RAP. McDaniel et al. (2000) confirmed the benefits of a tiered approach for incorporating RAP in asphalt mixtures. The tiers of design mentioned above are determined based on the RAP binder grade and the amount of RAP that is intended to be included (Bukowski, 1997). Tables 1.1 and 1.2 show that when RAP percentage is less than 15%, the virgin asphalt binder grade can be allowed to remain unchanged. When RAP percentage is in between 15 and 25%, the high and low temperature binder is "bumped" down by one grade, meaning the binder grade is reduced by one grade on both the high and low temperature end. When the proposed RAP percentage is above 25%, Superpave blending charts should be constructed to determine the desired virgin asphalt binder grade (Bukowski, 1997).

Different DOTs have adopted their own version of the tier system using a different range of RAP percentage for each tier. Twelve states (Texas not included) have raised the lower limit for selecting a softer virgin binder grade from 15 to 20 or 25 percent (Copeland, 2011). In these cases, no change to the binder grade is required when the RAP used is below this limit (which varies from 15 to 25% for different states). Different states also have different nomenclatures to define the percentage of RAP. Percent RAP may refer to percentage based on the weight of aggregate or weight of the total mix or weight of virgin binder replaced. The percentage of RAP used in the mix can be selected by determining

Table 1.1. Binder selection guidelines for RAP mixtures according to AASHTO M302 (2008)

Recommended Virgin Asphalt Binder Grade	Rap Percentage
No change in binder selection	<15
Select virgin binder one grade softer than normal (e.g., select PG58-28 if PG64-22 would normally be used)	15 - 25
Follow recommendations from blending charts	>25

Table 1.2. Binder selection guideline for RAP mixtures according to Superpave (2001)

Recommended Virgin Asphalt Binder Grade	Rap Percentage Recovered RAP Grade		
	PG XX-22 or lower	PG XX-16	PG XX-10 or higher
No change in binder selection	<20	<15	<10
Select virgin binder one grade softer than normal (e.g., PG58-28 if PG64-22 would normally be used)	20 - 30	15 - 25	10 - 15
Follow recommendations from blending charts	>30	>25	>15

the contribution of the RAP binder towards the total binder in the mix by weight.

For asphalt mixtures with higher RAP percentages, a blending chart must be constructed. This blending chart can then be used in two different ways. In the first approach, the percentage of RAP that will be used in an asphalt mix is known but the appropriate virgin asphalt binder grade for blending must be determined using Equation 1.1. In the second approach, the maximum percentage of RAP that can be used with a given asphalt mixture is determined using the same virgin binder grade using Equation 1.2.

There are several pieces of information that are needed to construct a blending chart. The physical properties and critical temperatures of the recovered RAP binder and the percentage of RAP in mixture or the physical properties of the virgin binder, depending on the design method. The critical grade temperature at high, intermediate, and low temperatures need to be considered for both designs to determine the virgin binder or RAP content satisfying the Equation 1.1 or Equation 1.2. The following subsections discuss in more detail the process of developing such blending charts.

$$T_{virgin} = \frac{T_{blend} - (\%RAP \times T_{RAP})}{(1 - \%RAP)} \tag{1.1}$$

$$\%RAP = \frac{(T_{blend} - T_{virgin})}{(T_{RAP} - T_{virgin})} \tag{1.2}$$

where:

T_{virgin} = Critical temperature of virgin asphalt binder (high, intermediate, or low).

T_{blend} = Critical temperature of blended asphalt binder (final desired) (high, intermediate, or low).

%RAP = Percentage of RAP expressed as a decimal.

T_{RAP} = Critical temperature of recovered RAP binder (high, intermediate, or low).

1.2.2 Binder recovery methods

A sample of the RAP binder is required in order to obtain the binder properties and critical temperature for the blending chart. Such a sample is obtained using a two step process referred to as extraction and recovery. Extraction refers to the process of separating the binder from the RAP mixture using a solvent. Recovery refers to the process of separating the binder from the solvent.

Various extraction methods exist that use different procedures, equipment, and solvents. Extraction processes are often criticized for their effect on the potential properties of binder and aggregates. Commonly used examples of extraction techniques include centrifuge, reflux, abson and Strategic Highway Research Program (SHRP) extraction method. Procedures such as AASHTO TP2 modified, ASTM D2172 method A,B,C, D, and E utilize some variation of these aforementioned extraction techniques. Previous study (Al-Qadi et al., 2009) reported the AASHTO TP2 method resulted in minimal aging to the recovered binder during the extraction process. The modified AASHTO TP2 method will be explained in more detail later in this section. Any given extraction method can also be carried out using any one of several different solvents, such as trichloroethylene (TCE), toluene, toluene/ethanol, or N-propyl bromide(NPB), and methylenechloride. Two main disadvantages of these extraction processes are excessive time consumption, and the use of toxic solvents that are both costly to purchase and dispose. As mentioned previously, the biggest limitation with extraction methods is the effect the process has on the properties of the binder. A study performed by Nosler et al. (2008) showed that there may be traces of solvent in the extracted binder and the impact of this trace can be observed in softening point, penetration and ductility.

Researchers have also employed the use of proxy RAP binder, which is aged virgin binder to "synthesize" RAP binder in an effort to avoid the influence of the extraction process. However, it is evident that such synthetic binders can only be used to study the influence of RAP binder on the performance of the blended binder and mixture in a laboratory environment. As such, this is not relevant to characterization of realistic RAP binders from the field.

A number of studies in the literature indicate that the SHRP procedure (AASHTO TP2 (1999) modified method) is the best extraction process that results in the least influence on the final properties of the binder ((Copeland, 2011); (Al-Qadi et al., 2009); (McDaniel et al., 2000) and (Bennert, 2012)). For example, McDaniel et al. (2000) compared the centrifuge extraction (ASTM2172 method A) and the AASHTO TP2 modified extraction procedure, which are the two most commonly used methods. For the centrifuge extraction, Abson recovery process was used, while the rotary evaporator (RE) method was used for recovery with AASHTO TP2 method. The recovered binder was characterized using the $G^*/sin\delta$ parameter. Their results showed that the centrifuge-abson-TCE method had lower values with the poorest repeatability. The centrifuge-RE-Toluene/Ethanol method had higher values indicating possible additional aging during the process. The standard rotary evaporator recovery procedure when compared to the modified AASHTO TP2 rotary evaporator recovery method involves the use of a higher temperature and lower vacuum. Lower temperature during the rotary evaporator process for the modified AASHTO TP2 method can help minimize hardening of the binder. Their study also revealed that the rotary evaporator recovery method was more consistent with coefficient of variation being much less compared to the abson recovery method (5-20% compared to 38-69%). However, AASHTO TP2 modified method is limited in the quantity per extraction process, which is about 50 grams.

The apparatus for the AASHTO TP2 method consists of an extraction vessel, centrifuge, rotary evaporator with oil bath, nitrogen gas, gas tubes, and vacuum pump.To briefly describe the extraction process, the RAP sample is mixed with a solvent in the extraction vessel while injecting nitrogen gas. After mixing the solvent in the vessel, it is extracted into a recovery flask under vacuum and then again into another recovery flask through a 0.020 mm cartridge filter all the while under vacuum. From the filtered solution, it is then introduced into the rotary evaporator recovery flask, beginning the primary distillation under vacuum at 100 ± 2.5°C. The process from the vessel to RE is repeated as many times as necessary with specified solvent quantity and mixing period. Once satisfactory solution dilution and volume is obtained, the solution is put through the centrifuge and then into the RE at a higher temperature until condensation rate is less than one drip per 30 seconds (McDaniel et al., 2000).

After the extraction process, the recovered asphalt is used to determine the upper and lower critical PG temperature using a dynamic shear rheometer (DSR) at high and intermediate temperatures, and using a bending beam rheometer (BBR) at low temperatures.

There are also questions regarding the exact contribution of RAP binder to total binder, but many researchers have demonstrated that asphalt mix designs with low RAP percentages (up to 15 to 20 percent) are not significantly affected by RAP variability (Bukowski (1997); Huang et al. (2005); Shah et al. (2007); Daniel and Lachance (2005); Li et al. (2008) and Roque et al. (2015)). However, considerable change in the performance of the asphalt mixture can be observed at higher RAP content and that the variability of the RAP has a greater influence on the performance of the mixture. For example, Daniel et al. (2005) reported that mixtures incorporating RAP had similar dynamic modulus and creep compliance compared to the control mixture containing 0% RAP. McDaniel et al. (2000) observed higher degree of blending for high quantity of RAP (40%) than low quantity of RAP (10%). These findings are reflected in the blending guidelines created by AASHTO and Superpave, in which no specific binder testing was required for low or intermediate RAP content, while a blending chart is required for high RAP content. The AASHTO and Superpave guideline further validate the assertion that low percentage of RAP (up to 20%) has no significant impact on the mixture, but higher RAP content is depended on the variability of RAP.

1.2.3 RAP and virgin binder blending

Before proceeding with further discussion on blending charts, it is important to briefly discuss the issue of blending of RAP and virgin binder in a mix. There are two extreme schools of thought regarding the blending of the RAP binder with the virgin binder. The first extreme scenario is that the RAP acts as a black rock with essentially no blending (or concomitant contribution) of the RAP binder with the virgin binder. In this case the benefits of RAP are realized purely from the recycling of the aggregates. The second extreme scenario is that the RAP and virgin binder completely blend to form a homogeneous mix. Studies show that reality is somewhere in between depending on the time and temperature at which the loose mix exists after being produced in the asphalt mix plant and prior to compaction and cooling. Current typical practice assumes the latter, i.e. 100 percent blending, which may be inaccurate. Research performed by Al-Qadi et al. (2009) found that the actual blending is somewhere in between complete blending and black rock but there is no direct method available to accurately determine the amount of blending that occurs.

Huang et al. (2005) conducted an extensive study to determine the blending ratio between virgin binder and RAP binder by studying the coating of mixed binder. Fine screened ($\leq$ No.4 sieve) RAP particles and coarse virgin aggregates (> No.4 sieve) were blended in order to visually differentiate and physically separate the particles after blending. Blending of the two types of particles allow RAP binder to be released and coat virgin aggregates and the coverage of binder on virgin aggregates could be observed. The asphalt content of RAP decreased from 6.8% to 6%. Also, their study showed a similar decrease in asphalt content for all RAP proportions (10-30%). Huang et al. (2005) concluded that majority of RAP binder is stuck on RAP aggregate and only small portion of the RAP binder blends. It should be noted that the mixing time and temperature were modified from current practice to facilitate improved blending. Huang et al. (2005) also performed a staged extraction to determine the penetration depth of virgin binder on RAP aggregate with aged binder coating. The asphalt viscosity increased at both high and intermediate temperature as the depth increased. Around 40% of the outer layer showed a decrease in stiffness with lower complex shear modulus while the inner layers (60%) showed stiffness resembling that of pure RAP binder.

Research by Shirodkar et al. (2011) extended the study of partial blending performed by Huang et al. (2005) by comparing the rheological properties of binder covering RAP aggregate and virgin aggregate. The theory was that full blending would result in similar properties of binder from virgin aggregate and RAP aggregate whereas, if there was no blending, then the properties of the binder coating the virgin aggregate would be more similar to virgin binder properties and RAP aggregate binder properties would be similar to properties of the RAP binder. The degree of partial blending was calculated using Equation 1.4. The study found that degrees of partial blending for 25% RAP with PG70-28 and 35% RAP with PG58-28 were 70% and 96%, respectively. So Shirodkar et al. (2011) concluded that Huang et al. (2005) may have underestimated degree of blending.

In a more recent study, Guo et al. (2016) studied the interaction between binder and mineral aggregate, including RAP, to better understand the behavior of different components. The role of individual ingredients of an asphalt mixture, i.e. asphalt binder and aggregates is clearly defined, however the interaction between those two components is not as well defined. Furthermore, the interaction of virgin binder and RAP aggregate is even less clear. Their study highlights the importance of understanding the influence of interactions at the binder-aggregate interface for warm mix asphalt with RAP. Guo et al. (2016) evaluated the effect of interfacial interactions under monotonically increasing shear load as well as under sinusoidal oscillation. An interaction parameter, indicating the degree of interaction between asphalt and aggregate showed that the mixing time and temperature significantly influence the interfacial properties of RAP aggregate surface (with a film of aged binder). Stronger interaction was observed as the curing temperature or time increased.

$$Blending\,ratio = \frac{(|(G^{*}/sin\delta)_{blend\,binder\,virgin\,agg}) - (G^{*}/sin\delta)_{blend\,binder\,RAP\,agg}|)}{(T_{RAP} - T_{virgin})} \tag{1.3}$$

$$Degree\,of\,partial\,blending\,(\%) = 100 \times |1 - Blending\,ratio| \tag{1.4}$$

The actual extent of the blending also varies depending on the source of the RAP, but the actual properties of the binder in mixtures containing RAP cannot be evaluated directly, as the process of extracting the binder results in complete blending of the virgin and RAP binder (Daniel and Mogawer, 2010). Therefore, testing must be performed on the mixtures to determine the effective binder properties.

In summary, RAP and virgin binder blend to varying degrees in an asphalt mixture. The degree of blending is dictated by the duration of blending, temperature of blending and properties of the RAP and virgin binder.

1.2.4 Mix design

There are several considerations that must be accounted for while designing a mix incorporating RAP. For example, the gradation of the RAP particles is not the original gradation of the aggregate used in RAP because the binder film on RAP adds to the dimension of the aggregate. Also, when establishing the gradation of RAP, it is possible that agglomerates of aggregates bound together by RAP binder appear as coarser particles. However, the gradation of the recovered RAP aggregate is used on an as-is basis for design purposes. Typical job mix formulas account for the differences in batching material gradation and the true gradation of the RAP material as well as for the binder contained in the RAP material (Copeland, 2011). The dust produced during the milling process is also a factor that limits the use of high RAP. Potential changes to the dust to asphalt ratio in the mix that may not be properly accounted for as well as the implications of this dust on air voids and VMA (Voids in Mineral Aggregate). Once RAP has been characterized, it is treated like any other aggregate stockpile for the purposes of developing an aggregate gradation.

One important recommendation for handling RAP in a laboratory environment is that RAP is heated before mixing with virgin materials to achieve the desired workability at a temperature of 110°C (230°F), but no more than 2 hours for a sample size of 1 to 2 kg. Higher temperature and longer than recommended heating times have been shown to change the properties of some RAPs (McDaniel et al., 2000).

1.2.5 Voids in mineral aggregate (VMA)

There is some variability associated with VMA of RAP included in asphalt mixes. Several studies have investigated the effect of RAP on the volumetric and mechanical properties of asphalt mixture with contradicting results. For example, Al-Qadi et al. (2009) studied six job mix formulas (JMF) with three different RAP sources at 0, 20, and 40 percent. For two of the RAP sources they reported increased VMA with increased RAP content. Daniel and Lachance (2005) also reported increased VMA with 25% and 40% RAP content. These researchers attributed this increase to the pre-heating of RAP material, which simulates real practice, to induce high ratio of blending between RAP binder and virgin binder. If not heated sufficiently, RAP particles behaved more like black rock rather than acting as an integral part of the mix with full blending. But they also found that overheating caused severe aging of RAP binder leading to less blending. Daniel and Lachance (2005) reported a decrease in VMA of 0.5 % when heating time increased from 2 to 3.5 hours, and an increase of 3% when the heating time was increased to 8 hours. Tran and Hassan (2011), on the other hand, found opposing results. Their study reported a decrease in VMA with increasing RAP content, evaluating 0, 10, 20, and 30% RAP with similar blending gradation. VMA decreased from 16.3 percent to 14.2 percent as RAP content increased from 0 to 30 percent. Such a decrease in VMA may be explained by the reduced design binder content and an increased amount of material passing through No. 200 sieve.

Paving using an asphalt mixture incorporating RAP should not be significantly different from paving a conventional asphalt mixture without RAP. The contractor should be aware that high RAP mixtures will have increased stiffness as a result of RAP. As such the contractor should take necessary steps during production to facilitate blending of RAP with virgin materials.

1.3 METHODS TO PREDICT PERFORMANCE OF RAP BINDER WITH INCREASED RELIABILITY

The gradation of the recycled aggregate changes during the milling process and the characteristics of the oxidized recycled binder needs to be captured during the mix design process. To characterize the aged binder from RAP, the binder needs to be extracted and the rheological properties need to be tested. Current practice only requires the rheological testing to determine the critical high and low temperature in order to determine the blending ratio of RAP and virgin material. However, after a thorough review of literature and field performance, it is clear that these binder tests do not completely capture the properties of the RAP binder and, consequently, the expected performance of the mix.

In particular, one of the main concerns of using RAP in an asphalt mixture is the propensity of the mixture to develop premature fatigue and/or thermal cracking. Therefore, it is critical to evaluate the cracking susceptibility of the RAP and virgin binder blend as a indicator for the expected cracking resistance of the mix. Previous studies have shown that the ductility of an asphalt binder is an excellent indicator of its ability to resist cracking in a mix. Researchers have also shown that several rheological indices can be derived that serve as a surrogate for the degree of brittleness and can be easily measured using the dynamic shear rheometer (DSR).

For example, Glover et al. (2005) proposed the rheological parameter, $G'/(\eta'/G')$, as an indicator of ductility based on a derivation of a mechanical analog to represent the ductility test consisting of springs and dashpots. It has been well demonstrated that the Glover parameter is directly correlated to the measured ductility for unmodified binders. The Glover parameter can be calculated based on DSR frequency sweep testing results, making it much more practical than directly measuring ductility using traditional methods. Rowe and Sharrock (2011) re-defined the Glover parameter in terms of $|G^*|$ and δ based on analysis of a black space diagram as shown in Equation 1.1 and suggested use of the parameter $|G^*| \times (cos\delta)^2/sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter.

$$\frac{G'/(\eta'}{G'} = \frac{|G^*| \times (cos\delta)^2}{sin\delta}\omega \tag{1.5}$$

Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep testing at 5, 15, and 25°C in the DSR and interpolating to find the value of G-R at 15°C and 0.005 rad/s to assess binder brittleness (Rowe et al., 2014).

A higher G-R value indicates increased brittleness. Another study relating binder ductility to field block cracking and surface raveling, proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking potential (Anderson et al., 2011).

In addition, of the G-R parameter, recent studies have also shown that the ΔT_c parameter, related to low temperature properties, is also a good predictor of cracking susceptibility. The ΔT_c parameter is the difference in the critical low temperature based on the stiffness (S) criterion and the critical low temperature based on the m-value criterion. Therefore, this parameter can also be used as an indicator of potential fatigue cracking because it is also correlated with intermediate temperature fatigue cracking resistance (e.g., as measured using the overlay tester).

The third indicator for fatigue cracking resistance is based on conducting time sweep tests. The time sweep test was developed in NCHRP 9-10 (Bahia et al., 2001) in an attempt to overcome the limitations of the current PG specification. The time sweep test consists of applying repeated cyclic loading at fixed amplitude to an 8 mm diameter asphalt binder specimen in the DSR. Changes in loading resistance with respect to number of loading cycles are used to evaluate damage resistance and determine fatigue failure. It has been demonstrated that results of binder time sweep testing are correlated with mixture beam fatigue results (Bahia et al., 2001) and direct tension testing (Hintz, 2012). However, the time sweep has been deemed impractical for specification due to the need to select an appropriate loading amplitude for testing to produce failure in a reasonable amount of time, which requires knowledge of the material's damage resistance a priori.

The LAS test (AASHTO TP101, 2014) has been proposed as a surrogate to the time sweep as a practical specification test (Johnson (2010); Hintz et al. (2011); Hintz and Bahia (2013)). The LAS test is similar to the time sweep in that it consists of cyclic loading in the DSR and utilizes the same specimen geometry. However, in the LAS test, loading amplitudes are systematically increased to accelerate damage. The LAS test also includes a frequency sweep to obtain a fingerprint of the material's undamaged material response, which can be run directly before the amplitude sweep, on the same specimen. Total testing time, including thermal equilibration, is approximately 30 minutes. Simplified Viscoelastic Continuum Damage (S-VECD) theory can be applied to LAS (or time sweep) results to allow for estimating fatigue life at any strain amplitude of interest. Fatigue life predictions using this newly developed failure criterion coupled with the S-VECD model are able to predict measured time sweep fatigue lives reasonably well.

Fatigue life predictions generally related well with the field fatigue performance measured in the FHWA-ALF study (Wang et al., 2015), as well as LTPP field performance (Hintz et al., 2011). It has also been demonstrated that when a strain ratio from mix to binder of 80 is used, fatigue life predictions from LAS results are consistent with mixture fatigue life predictions (Safaei et al., 2014).

Finally, in addition to cracking resistance, it is important to asses the rutting resistance and elastic recovery of asphalt binder with and without RAP. To this end, the PG specification $G*/sin(\delta)$ parameter can be used to assess the rutting resistance. However, according to studies from the last few years, the correlation between $G^*/sin\delta$ and measured rutting in asphalt mixtures has been shown to be weak (Bahia et al., 2001). The repeated creep and recovery test using the DSR was explored as an alternative. The outcome of these investigations was the development of the Multiple Stress Creep and Recovery (MSCR) test protocol to measure the non-recoverable compliance of the binder J_{nr}. The strain parameter ε_{10} was defined as the non-recoverable strain at the end of a 9 second recovery period after one second loading period. At a given temperature, a binder with a higher value of J_{nr} indicates a higher propensity to accumulate permanent deformation. D'Angelo (2007) also reported that J_{nr} values correlated better with rutting compared to the $G^*/sin\delta$ parameter as prescribed by the original Superpave PG specification. This finding was later substantiated by other researchers (Bukowski et al. (2011), DuBois et al. (2014) and Guo et al. (2016)).

1.4 PRACTICE FOR BINDER SELECTION IN TEXAS

TxDOT standard specifications currently allow the use of RAP in all asphalt concrete mixtures with the exception of thin overlay mixtures (TOM) and crack attenuating mixtures (CAM). The maximum allowable percent of RAP by weight is limited to 30% when the mixture is used as a base or binder (level-up) course and 20% when used as the surface course. Special provisions were recently approved that allow both unfractionated and fractionated RAP to be used without requiring a plan note. Unfractionated RAP is limited to 10% for surface mixes, and 20% for base mixes. Currently some districts in Texas do not allow RAP to be used in an asphalt mixture or in the surface mixes mainly because of the high variability associated with these mixes. Other barriers to increasing the use of RAP in Texas (and in the US) include:

- the need to meet voids and asphalt content with Superpave mix designs,
- the need to meet skid requirements,

Table 1.3. Allowable substitute PG binders and maximum recycled binder ratios. Note: Table 5 in TxDOT specification book 2014 (TxDOT, 2014)

Originally Specified PG Binder	Allowable Substitute PG Binder	Maximum Ratio of Recycled Binder to Total Binder (%)		
		Surface	Intermediate	Base
		HMA		
76-22	70-22 or 64-22	20.0	20.0	20.0
	70-28 or 64-28	30.0	35.0	40.0
70-22	64-22	20.0	20.0	20.0
	64-28 or 58-28	30.0	35.0	40.0
64-22	58-28	30.0	35.0	40.0
76-28	70-28 or 64-28	20.0	20.0	20.0
	64-34	30.0	35.0	40.0
70-28	64-28 or 58-28	20.0	20.0	20.0
	64-34 or 58-34	30.0	35.0	40.0
64-28	58-28	20.0	20.0	20.0
	58-34	30.0	35.0	40.0
		WMA		
76-22	70-22 or 64-22	30.0	35.0	40.0
70-22	64-22 or 58-28	30.0	35.0	40.0
64-22	58-28	30.0	35.0	40.0
76-28	70-28 or 64-28	30.0	35.0	40.0
70-28	64-28 or 58-28	30.0	35.0	40.0
64-28	58-28	30.0	35.0	40.0

- hardness of asphalt with high RAP contents potentially, leading to fatigue cracking, with the subsequent need to use softer binders that could potentially lead to rutting problems,
- uncertainty regarding use of RAP with special mixtures, for example SMA,
- uncertainty regarding use of RAP with polymers, and
- plant restrictions.

Table 1.3 shows the TxDOT specification for the originally specified binder, allowable substitute binder, and the maximum ratio of recycled binder to total binder for a surface, intermediate or base layer of a mixture.

In summary, recycled materials are typically used in conjunction with warm mix technologies, recycling agents, and a softer substitute binder. The recycled binder ratio (RBR) is controlled through "Table 5" in Specification 2014 Items 340/341/344. However, the current specification (1) may result in the substitution of a polymer modified binder with a binder that has little or no polymer (elastomer), (2) does not account for the influence of recycling agents, and (3) does not address the potential differences in the quality of binders from different sources of RAP or RAS. Also note that this table allows for binder substitution regardless of the percentage of RAP, which is different from the general trend of using the same grade up to typically 20% RAP. Furthermore, in many instances the grade lowering is restricted to only the higher grade and not the lower grade.

1.5 OBJECTIVE

The objective of this study was to revisit the allowable percentages of RAP and grades of substitute binders as shown in Table 1.3. Specifically, the goal of this work was to examine this table using two field mixtures with a mix design that is without RAP and uses a higher binder grade as well as a design with RAP and a substitute lower binder grade. Performance tests using binder and mixtures were conducted to evaluate the influence of RAP and binder substitution. Chapter 2 of this thesis presents additional details for the methodology and materials used, Chapter 3 presents the results followed by conclusions in Chapter 4.

CHAPTER 2. METHODOLOGY AND MATERIAL SELECTION REVIEW

2.1 OVERVIEW

This chapter provides an overview of the binder and mixture tests performed and the methods used to fabricate test specimens. A number of testing devices were utilized to characterize binders and mixtures and recycled materials. A Dynamic Shear Rheometer (DSR) and a Bending Beam Rheometer (BBR) were used to obtain the characteristics of the different binders (virgin, recycled or a combination of the two). This study evaluated the selected binders in unaged, short-term and long-term aged conditions by performing laboratory simulation of short and long-term aging using Rolling Thin Film Oven (RTFO) and Pressure Aging Vessel (PAV), respectively. A Hamburg Wheel Tracking Device (HWTD), an electro-hydraulic system device (Instron), and an Indirect Tensile Test (IDT) device were used to evaluate different mixture combinations (with and without RAP). The full asphalt mixture specimens were compacted using a Superpave Gyratory Compactor (SGC).

2.2 CURRENT PRACTICE

As detailed in Chapter 1 Literature Review, the current practice of allowing a substitute binder with recycled material (RAP or RAS) in new asphalt pavement in Texas is controlled by 'Table 5' in TxDOT Specification Item 340, 341, and 344 which are specifications for Dense-Graded Hot-Mix Asphalt (small quantity), Dense-Graded Hot-Mix Asphalt, and Superpave Mixtures, respectively.

The table lists a total of nine different grades of of binders with allowable substitutions and RAP percentages for hot-mix asphalt (HMA) and warm-mix asphalt (WMA). Of these nine different performance grades (PG), the three most commonly used in HMA and WMA production are PG 64-22, 70-22, and 76-22. To further explain the table, the originally specified binder (the first column of table 5) is the binder that a TxDOT engineer would normally assign for a specific job. The substitute binder is a lower grade PG binder that can be used in place of the specified binder when RAP is included in the mix. Finally, ratio of recycled binder to total binder is the ratio of binder from recycled material, such as RAP and RAS, to the total binder, i.e virgin binder and binder from the recycled material. The rational for allowing a softer substitute binder is that the binder from RAP and/or

RAS has a much higher stiffness compared to the virgin binder due to oxidative aging that occurs during its service life. Therefore, using a softer binder with lower high temperature grade can help to compensate this. However, there are several important aspects that are implicitly assumed or allowed by this approach.

- The approach assumes that recycled binder from any source is the same grade and quality. In reality, binders from recycled materials vary significantly from one source to another.
- The use of a lower substitute grade allows the use of binders that may have lower quality requirements. For example, a PG 70-22 has a high elastic recovery requirement where as a substitute binder grade, such as the PG 64-22, does not.

2.3 BINDER TESTING

2.3.1 Material selection and sample fabrication

To study the influence of mixing recycled binder with virgin binder, different proportions of recycled binder were mixed with virgin binder. Recycled binder from recycled material was obtained through an extraction and recovery process after which, the recycled binder was mixed with different proportion of virgin binder. Based on the current practice of RAP presented in the previous section and the goals of this study, the following testing categories of binders and binder combinations were prepared for further evaluation:

- Specified virgin binder originally intended for use before substitution (representing the binder properties that engineers expected without RAP and substitution)
- Substitute virgin binder (representing the baseline properties corresponding to the binder that was actually used)
- Substitute virgin binder + RAP extracts(% as JMF) (representing the properties of the binder similar to what exists in the mix)
- Substitute virgin binder+ RAP/RAS extracts(% as JMF +10% additional) (representing the properties of binder in a hypothetical case with high proportion of RAP)

2.3.2 Binder extraction

An extraction process was performed to obtain the recycled binder from the recycled material for binder testing. There are number of extraction methods, as mentioned in the literature review (Chapter 1). This study utilized the Centrifuge-Rotary evaporator (RE) with an oil bath and silicon as the heating medium for recovery and toluene as the extraction solution. The centrifuge and RE were both performed under a fume hood due to the use of toluene as the extraction solvent. The primary centrifuge used for this study was the Gilson Company, Centrifuge Extractor shown in Figure 2.1.

Figure 2.1. Centrifuge: Gilson Company, centrifuge extractor

The procedure used with the Centrifuge was as follows:

1. A sample of recycled material (1,500 kg) was obtained along with a flask for receiving the centrifuged solution, stopper for the flask, beaker, 4.0 μm filter, and toluene.

2. The recycled material was placed inside the bowl for extraction.

3. 800 ml of toluene was measured in a beaker and poured carefully into the bowl with the recycled material. The bowl was carefully stirred ensuring no solution or material leaves the bowl and the solvent thoroughly wets the material inside the bowl.

4. The centrifuge was properly closed and set aside for one hour to allow the solvent to fully soak all material.

5. The lid of the centrifuge was removed and a 4.0 μm filter was placed. The lid was then closed using a ranch to ensure a tight lock of the lid and the bowl.

6. The solution was centrifuged into a flask until solution stopped pouring out of the tube. the flask was sealed with a stopper.

7. Step 3, 4, 5, and 6 were repeated at least two more times or until But as many as necessary for the recycled material to be without any asphalt binder.

Figure 2.2. Centrifuge with aggregates after the first run of extraction

The solution obtained from the Centrifuge was then used with the rotary evaporator (RE), as shown in Figure 2.3, to recover the asphalt binder from toluene solution. The RE used for this study was the Cole-Parmer Rotary Evaporator

The procedure used with the RE was as follows:

1. The oil bath was set to reach a temperature of 80°C.

2. 500 mL of binder-toluene solution was poured inside a boiling round flask using a funnel and the flask was placed onto the RE lip.

3. Water was run through the RE and all vacuum release valves were closed to ensure vacuum.

4. The vacuum pump was turned on to reach a vacuum of 62 cm Hg.

5. The RE was lowered to a height so that the solution inside the round flask was fully submerged in the oil bath and rotated (shown detailed picture in Figure 2.3).

6. The solution was closely observed to prevent bumping.

7. The temperature was raised accordingly to maintain a visible flow of toluene (typical process of RE is shown in Table 2.1).

8. When there was no more visible trace of toluene inside the flask, the flask was raised out of the oil bath, the vacuum pump was turned off, the vacuum was released and remaining extracted binder was removed out of the flask into a metal can.

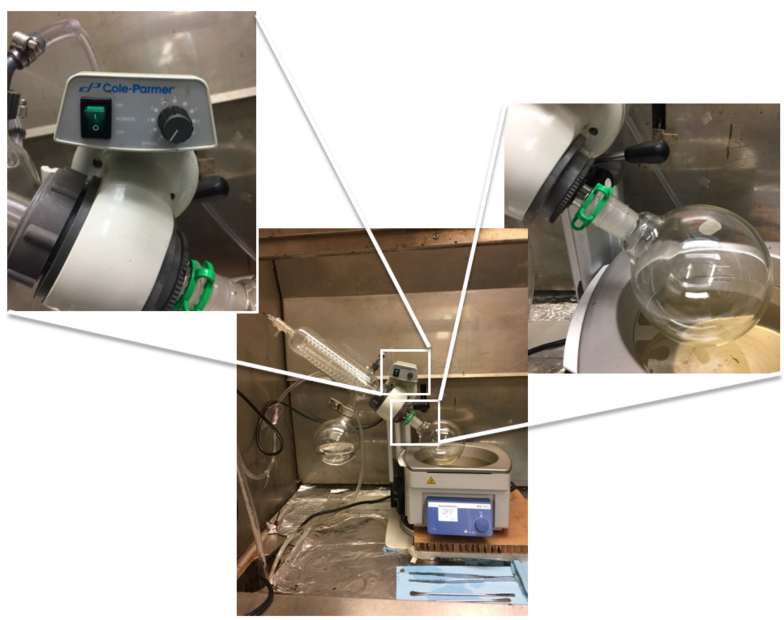

Figure 2.3. Detailed figure of the rotary evaporator

Table 2.1. Rotary evaporator process

Time, min	Bath Temperature, °C	Rotation Speed	Vacuum Pressure, cm Hg.
0	80	4	62
10	80	4	62
30	85	4	62
39	85	4	62
45	90	4	64
50	90	4	64
59	90	4	64
63	90	4	64
75	95	4	64
78	100	4	64
81	105	4	64
84	110	4	64
87	115	4	64
90	120	4	64
93	125	4	64
96	130	4	64
99	135	4	64
102	140	4	64
105	150	4	64
108	155	4	64
111	160	4	64
114	165	4	64
117	165	4	64
120	165	2	64
130	165	2	64

2.3.3 Blending

A high shear mixer was used to blend the virgin binder with recycled binder. The virgin binder and recycled binder were preheated in an oven, typically less than 30 minutes. This allowed the binder to become fluid and then the high shear mixer was used to mix the binder at the temperature of 160°C for one hour at 2,400 rpm.

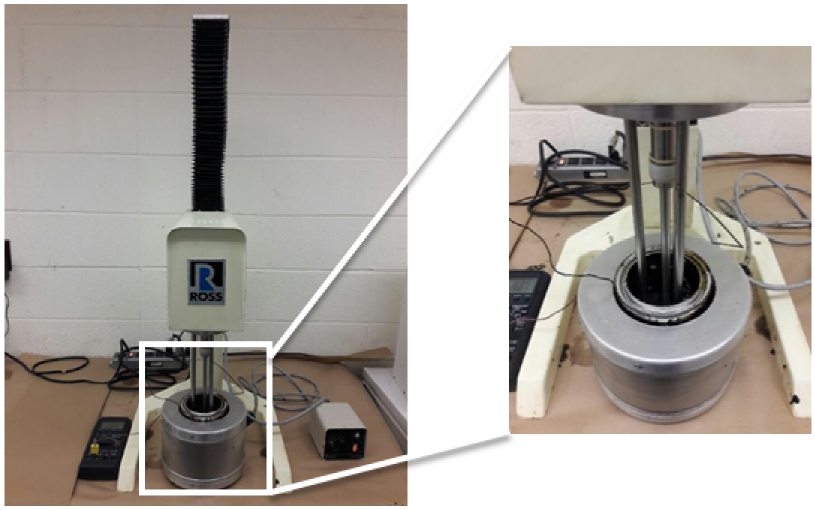

Figure 2.4. High shear mixer

2.3.4 Short-term aging

The Rolling Thin-Film Oven (RTFO) is intended to simulate short-term aging of the binder that it experiences during the initial phases of asphalt life cycle, including aging that occurs during the mixture production at the asphalt mix plant as well as aging that occurs during storage and transport to the construction site and during compaction at the site. The test involves a moving film of asphalt binder in an open bottle placed in a rotating circular rack in an oven for 85 minutes at 163°C with heated air blowing into each bottle at the rate of 4000 mL/min at the lowest point of travel. The ASTM D2872 (2012) procedure was followed for the RTFO aging process using the James Cox & Sons Rolling Thin Film Oven, Model CS 325, as seen in Figure 2.5.

2.3.5 Long-term aging

Pressure Aging Vessel (PAV) method is intended to simulate long-term aging of the binder experienced through the pavement service life. The oxidation that the binder will experience is simulated by placing 50 grams of RTFO aged binder as a thin film in a steel pan, and then placing the pan in the PAV under 2.1 MPa of pressure for 20 hours at 100°C. For this study, the ASTM D6521 (2013) procedure was followed for the long-term aging process using the Pretex Pressure Aging Vessel by the Gilson Company, as seen in Figure 2.6.

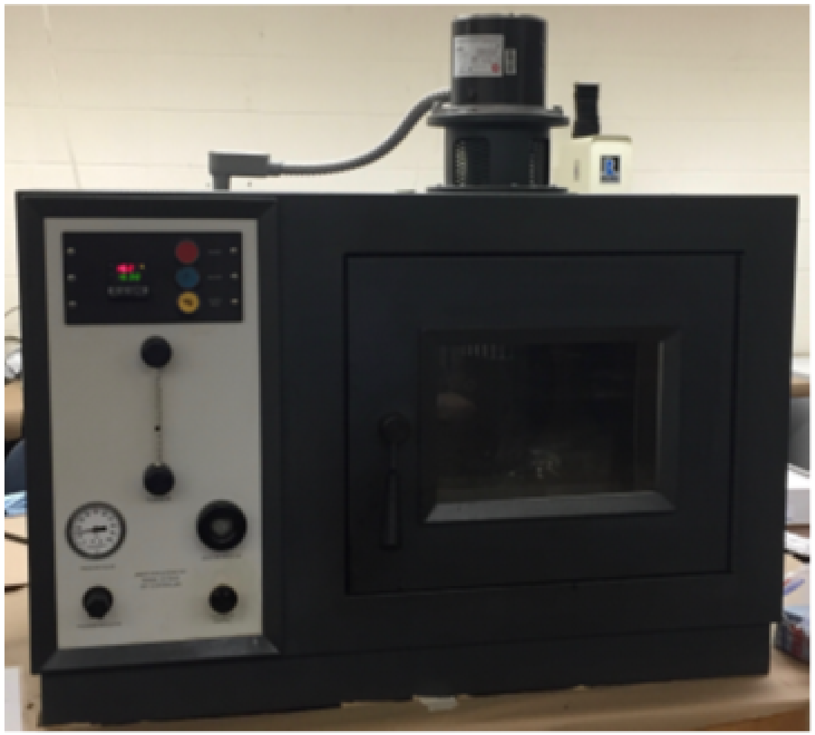

Figure 2.5. Rolling Thin Film Oven: Model CS 325

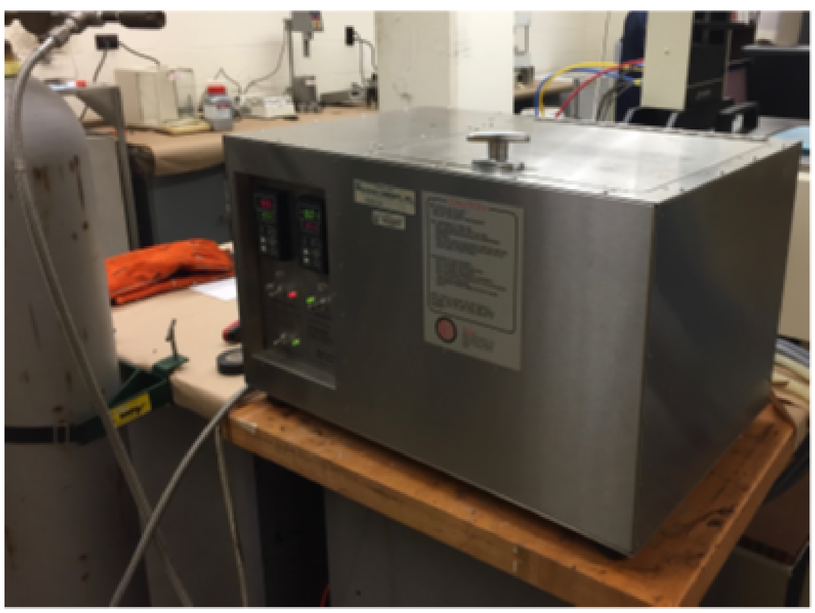

Figure 2.6. Pressure Aging Vessel: Gilson Company

2.4 RHEOLOGICAL MEASUREMENTS AT HIGH TEMPERATURE

A Dynamic Shear Rheometer (DSR) is typically used to determine the dynamic shear modulus and phase angle of the asphalt binder by applying oscillatory shear stress using two circular plates where the upper plate oscillates across the sample to create a shearing action at a specific frequency while the bottom plate is fixed.

The plate diameter can be altered to test binders with varying stiffness at different temperatures. When the specimen is stiff or requires testing at low temperature, a 8 mm (0.315 inches) diameter plate can be used. PAV residue is tested at lower temperature using a 8 mm plate while unaged and RTFO residue are tested at high temperatures using a 25 mm diameter plate. The standard testing for DSR is suitable for binder with dynamic shear modulus arranging from 100 Pa to 100 MPa. This range in modulus is typically obtained between 4 to 88°C depending upon the grade, test temperature, and aging of the asphalt binder (ASTM D7175, 2015). The DSR used for this study was Discovery HR-2 Hybrid Rheometer shown in Figure 2.7.

In this study, the fundamental properties of the binder were measured and complete characteristics were determined using the DSR and the following test methods:

- Short time sweep test to obtain the true high grade of the binder by measuring the complex modulus G^* and phase angle δ
- Multiple Stress Creep and Recovery (MSCR) test to obtain the non-recoverable creep compliance J_{nr} and percent recovery R%
- Frequency sweep test to obtain the Master Curve at any measured reference temperature

2.4.1 Performance grading system

First, the tests related to the Superpave Performance Grade (PG) system were conducted following AASHTO M320 (2017). The parameter $G^*/sin\delta$ was measured for both unaged and short-term aged binders at high temperature. The stiffness of the binder is represented by the complex modulus G^* while the elasticity of the binder is represented by the phase angle δ. The final parameter, $G^*/sin\delta$, quantifies rutting resistance of the binder. The parameter is obtained for both unaged and short-term aged binders. Both unaged and short-term aged binders were tested at three different high temperatures to obtain $G^*/sin\delta$

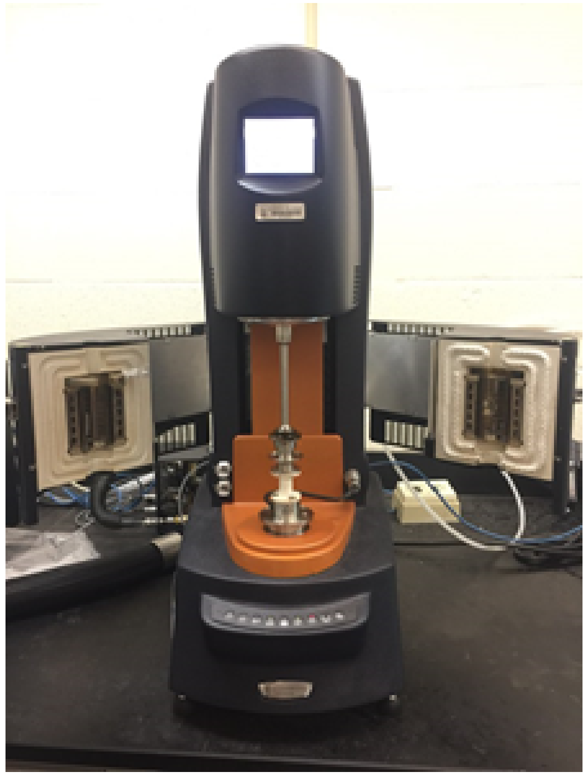

Figure 2.7. Discovery HR-2 Hybrid Rheometer

by applying a cyclic shear stress following a sinusoidal wave at a frequency of 10 rad/s. The three temperatures were the PG high grade as rated by the supplier and 6°C above and below that high grade. So the three different temperatures tested for binders varied depending on the high grade of the binder. All time sweep tests were performed twice with a replicate sample to validate its repeatability. In total, two tests were performed and the average of the two was used for further analysis. The measured values of $G^*/sin\delta$ at three different temperatures were used to obtain a log-linear relationship with temperature. The standard PG system limits $G^*/sin\delta$ for unaged and short-term aged binders to 1.00 kPa and 2.20 kPa, respectively, so the temperature at which the binders reached 1.00 kPa and 2.20 kPa were interpolated from the data as the continuous high grade. A typical result for log $G^*/sin\delta$ versus temperature is displayed in Figure 2.8. The final true high grade is the lower of the two values obtained using the unaged and RTFO aged binders for design purposes. Then, the PG grade is rounded down to the nearest grade in increments of 6°C. The parameter $G^*/sin\delta$ was obtained for two reasons. First, to verify the grade of the binder as rated by the producer. Second, and more importantly, to identify the true grade or continuous grade of the binder. Identifying the continuous grade of binder is important because this value can vary significantly within the 6°C window used in the PG system and the effect of adding recycled binder needs to be observed closely.

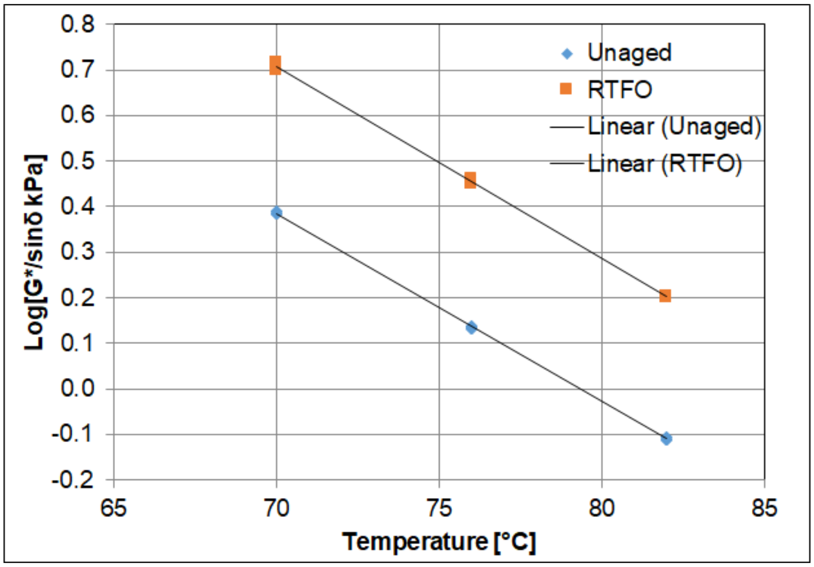

Figure 2.8. Typical graph of log $G^*/sin\delta$ versus time

2.4.2 Multiple stress creep and recovery test

As mentioned previously, in order to comprehensively characterize the binder, different tests were performed in this study. This section explains the Multiple Stress Creep and Recovery (MSCR) test that was utilized to capture the ability of the binder to resist rutting. The parameter to determine rutting resistance in the current PG system, $G^*/sin\delta$ has been criticized for its inability to accurately predict rutting resistance, particularly for polymer modified binders. For example, Bahia et al. (2001) found that $G^*/sin\delta$, and rutting had a weak correlation to rutting resistance and Behnood (2016) found the current specifications (AASHTO M320 (2017)) to inaccurately predict the rutting characteristics of modified asphalt binders, especially at high temperatures. On the other hand, MSCR has been well documented in previous research to provide a better correlation to rutting compared to $G^*/sin\delta$ (AASHTO TP70, 2009). For example, studies by Zhou et al. (2014), Bukowski et al. (2011), D'Angelo (2010), and Dubois et al. (2014) confirmed that the MSCR test has improved correlation to the ability of the binder to resist permanent deformation. Also, the binder's response in the MSCR test was found to be significantly different than the response in the existing PG test (Behnood, 2016). An additional advantage of the MSCR test is that it also provides a direct measure of the elastic recovery of the binder. Elastic recovery, in turn, is correlated with rutting resistance and it also serves as an indicator for cracking resistance. The MSCR test method determines the percent of recovery and non-recoverable creep compliance of asphalt binders which is intended to provide a means to determine the presence of elastic response and stress dependence of asphalt binders.

The specimen was loaded with a constant creep stress at 100 Pa for 1 second duration, followed by a zero-stress recovery for a 9 second duration. The stress and strain data were recorded at least every 0.1 seconds for the creep cycle and at least every 0.45 seconds for the recovery cycle on a running accumulated time along with a data point at 1 and 10 seconds for each cycle's local time. With no rest period between cycles, the creep and recovery cycle was repeated nine times for a total of ten cycles. After a total of ten cycles, with no rest period, the ten cycles of creep and recovery were repeated with a higher load of 3200 Pa. The testing procedure followed was according to AASHTO TP70 (2009). For MSCR, similar to $G^*/sin\delta$, each binder was evaluated at three temperatures, using three different specimens at the high PG grade temperature and one grade above and below. So, the three different test temperatures varied depending on the specified PG grade of the binder. Finally, all MSCR tests were performed twice with a replicate sample to validate its repeatability. In total, two tests were performed and the average of the two was used for further analysis. A typical output from the MSCR test is shown in Figure 2.9.

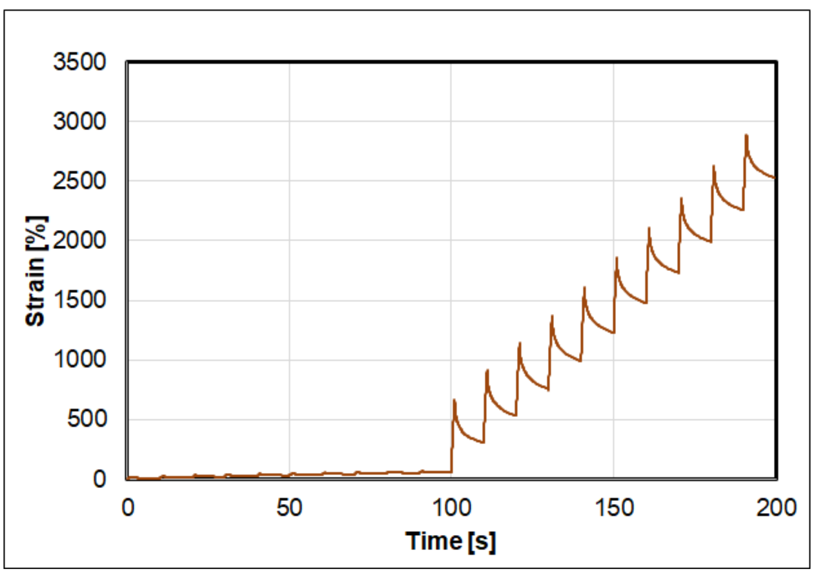

Figure 2.9. Typical result from the MSCR test

The parameters derived from the MSCR test to characterize the asphalt binder's properties are the percent recovery (R%) and non-recoverable creep compliance (J_{nr}). The percent recovery is the deformation recovered during the rest period averaged over all 10 cycles. The non-recoverable creep compliance is the ratio of the permanent strain to the applied stress level.

In order to calculate the two parameters for MSCR, the strain data must be adjusted as shown below. This is because the test is a continuous creep test and the measured strain in cumulative. Let ε_1 denote the adjusted strain value at the end of the creep portion of each cycle, ε_0 denote the initial strain value at he beginning of the creep portion of each cycle and ε_c denote the strain value at the end of the creep portion of each cycle. Equation 2.2 can be used to calculate ε_1.

$$\varepsilon_1 = \varepsilon_c - \varepsilon_0 \tag{2.1}$$

Next, ε_{10} denoting the adjusted strain value at the end of the recovery portion of each cycle, is computed as the difference between ε_r denoting the strain value at the end of the recovery portion of each cycle and ε_0

$$\varepsilon_{10} = \varepsilon_r - \varepsilon_0 \tag{2.2}$$

Lastly, the percent of strain recovery at the creep with stress level of 3.2 kPa and 0.1 kPa for cycle N are denoted as ε_r (3.2, N) and ε_r (0.1, N), respectively.

$$\varepsilon_r(3.2, N) = \frac{(\varepsilon_1 - \varepsilon_{10}) \times 100}{\varepsilon_1} \tag{2.3}$$

$$\varepsilon_r(0.1, N) = \frac{(\varepsilon_1 - \varepsilon_{10}) \times 100}{\varepsilon_1} \tag{2.4}$$

Using the adjusted strain to calculate the percent recovery for all 10 steps, the average percent recovery following the 0.1 kPa and 3.2 kPa stress level can be calculated by taking a simple average of the ten cycles.

$$R_{0.1} = \frac{\sum_{n=1}^{10} \varepsilon_r(0.1, N)}{10} \tag{2.5}$$

$$R_{3.2} = \frac{\sum_{n=1}^{10} \varepsilon_r(3.2, N)}{10} \tag{2.6}$$

The non-recoverble creep compliance, J_{nr}, for 0.1 kPa and 3.2 kPa stress levels were also calculated using the adjusted strain at the end of the recovery portion of each cycle divided by stress level. The final J_{nr}, kPa^{-1}, is the average of all 10 cycles. An important assumption that must be highlighted regarding the non-recoverable creep compliance is that the parameter is based on residual strain at the end of each cycle lasting for 10 seconds. This residual strain may or may not be the total plastic or non-recoverable strain associated with the applied stress level and some binders may continue to recover and reduce the plastic strain well past the 9 seconds of recovery.

$$J_{nr}(0.1,N) = \frac{\varepsilon_{10}}{0.1} \tag{2.7}$$

$$J_{nr}(3.2,N) = \frac{\varepsilon_{10}}{3.2} \tag{2.8}$$

$$J_{nr0.1} = \frac{\sum_{n=1}^{10} J_{nr}(0.1,N)}{10} \tag{2.9}$$

$$J_{nr3.2} = \frac{\sum_{n=1}^{10} J_{nr}(3.2,N)}{10} \tag{2.10}$$

Also, the percent difference in nonrecoverable creep compliance between 0.1 kPa and 3.2 kPa, $J_{(nrdiff)}$, %, is calculated using the following Equation 2.2. The percent difference of the two stress levels serves as an indicator of the dependency on the stress level of the asphalt binder.

$$J_{(nrdiff)} = \frac{(J_{nr3.2} - J_{nr0.1})}{J_{nr0.1}} \tag{2.11}$$

The AASHTO TP70 (2009) standard for MSCR test of asphalt binder suggests a relationship that can be used as an indicator for the presence of an elastomeric polymer. The relationship is between the average percent recovery at 3.2 kPa, $R_{3.2}$ and the average nonrecoverable creep compliance at 3.2 kPa, $J_{(nr3.2)}$. If the tested binder falls above this relationship curve, then the binder is generally regarded as adequately modified with an acceptable elastomeric polymer. On the other hand, if the tested binder is plotted below the curve (see Figure 2.10), the indication is that the asphalt binder is not modified with an elastomeric polymer.

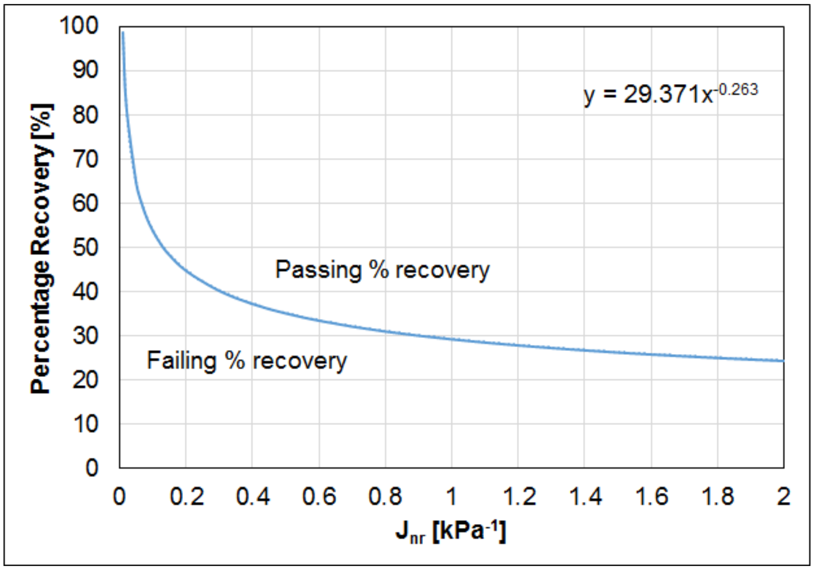

Figure 2.10. Nonrecoverable creep compliance versus percent recovery

2.4.3 Glover-Rowe parameter

The Glover-Rowe (G-R) parameter was also obtained using the DSR to characterize the properties of the binder in this study. Glover et al. (2005) reported from previous studies that fatigue and low temperature cracking in the field were strongly correlated with the ductility of the asphalt binder. In their study, they also demonstrated that the rheological parameter $G'/(\eta'/G')$ was correlated with the ductility of the binder. Based on this, they proposed using this parameter, $G'/(\eta'/G')$, as an indicator for cracking resistance of asphalt binder. However, they also noted that this surrogate parameter may not be an accurate indicator for polymer modified binders. Rowe proposed a new parameter by redefining the Glover parameter in terms of $|G^*|$ and δ based on analysis of a black space diagram and suggested the use of the parameter $|G^*| \times (cos\delta)^2/sin\delta$, termed the Glover-Rowe (G-R) parameter in place of the original Glover parameter.

Later, Rowe proposed measuring the G-R parameter based on construction of a master curve from frequency sweep testing at 5 $°C$, 15°C, and 25°C in the DSR and interpolating to find the value of G-R at 15°C and 0.005 rad/s to assess the ductility of the binder (Rowe et al., 2014). A higher G-R value indicates increased brittleness and Rowe proposed that a G-R parameter value of 180 kPa corresponds to damage onset whereas a G-R value exceeding 450 kPa corresponds to significant cracking potential based on a study relating binder ductility to field block cracking and surface raveling by Anderson et al. (2011).

In this study, a frequency-temperature sweep was conducted for each binder sample. The frequencies used were from 15 Hz to 0.02 Hz and the temperatures used were 5 °C, 15 °C , 25 °C. The resulting data were shifted to form a single curve at a reference temperature. The thermo-rheological-simple property of a binder permits a horizontal shift on the log frequency axis because the complex modulus is self-symmetric at different temperatures. By shifting the modulus obtained at different temperatures, a master curve was obtained. The shifted curve is fitted into a mathematical form that best represent the shape of the data. A sigmoidal function, shown in Equation 2.12, was selected as the fitting model for this study because it is a common model used in the area of asphalt materials. The terms α thru δ in the equation are shape parameters and ω is the angular frequency.

$$log|G^*|(\omega) = \delta + \frac{\alpha}{1+e^{\beta+\gamma log\omega}} \tag{2.12}$$

Figure 2.11 shows a typical result from a frequency sweep test. The master curve was developed for both storage modulus, $G^{'}$, and loss modulus, $G^{''}$, to obtain the G-R parameter. Utilizing the master curve, the $G^{'}$ and $G^{''}$ at 0.005 rad/s was determined to obtain the G^* and δ at 15°C and 0.005 rad/s. The G-R parameter was then computed using Equation 2.13 can be calculated.

$$\frac{|G^*|\times(cos\delta)^2}{sin\delta} \tag{2.13}$$

2.5 RHEOLOGICAL PROPERTIES AT LOW TEMPERATURE

A Bending Beam Rheometer (BBR) was used to measure the creep stiffness and m-value (slope of the stiffness versus temperature log-log plot) to obtain the true low temperature grade and observe the binder's ability to resist stress and relax internal stresses to prevent thermal cracking. The primary device used for this study was the Cannon TE-BBR (Thermoelectric Bending Beam Rheometer). The device uses a thermoelectrically cooled bath with methanol as the medium to achieve temperatures from 0 to -40°C. It uses a three-point loading system with two supports and one point of load application. The load shaft applies a programmed load at the midpoint and the deflection at that point is measured to calculate the beam stiffness, stress, and strain using the simple beam theory. Stiffness is measured as a function of time using Equation 2.14. The m-value is obtained by plotting stiffness values versus time on a log-log scale. The slope of this plot at 60 seconds is

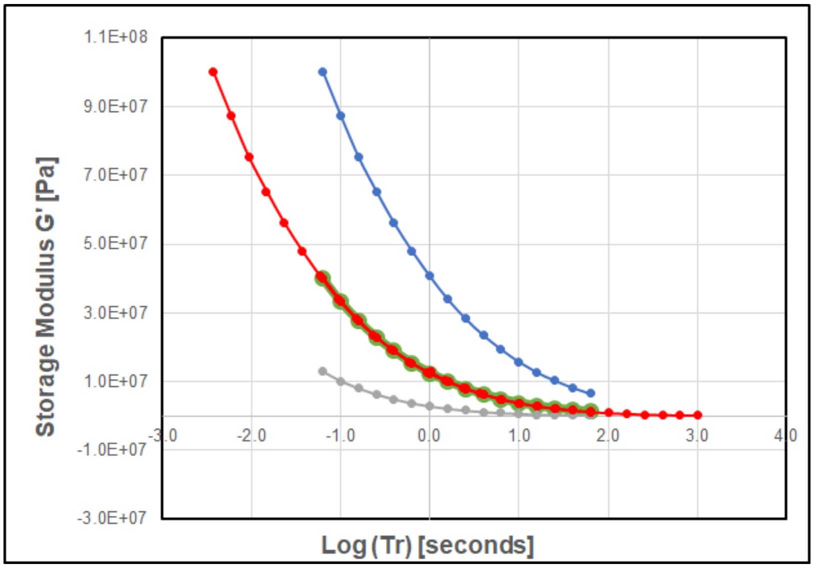

Figure 2.11. Typical graph of storage modulus versus log time with master curve

the m-value of the binder and it reflects the binder's ability to relax stresses over time under constant deformation. The AASHTO M320 (2017) specifies the stiffness of an asphalt binder to a maximum of 300 MPa, and the m-value to a minimum of 0.3 at the specified low temperature grade of the binder. Stiffness and m-value are obtained by testing long term aged binder from the PAV, which represents the worst case scenario for thermal cracking.

$$S(t) = \frac{PL^3}{4bh^3\delta(t)} \tag{2.14}$$

For this study, the BBR creep test was performed according to AASHTO T313 (2011) specifications using a beam made of asphalt binder with a length of 127.0 mm, a height of 12.5 mm, and a thickness of 6.25 mm. The load applied has a magnitude of 980 mN and the deflection response of the beam was measured upon application of the load. All BBR tests were conducted at three different temperatures: 10°C higher than the the PG low grade provided by the producer, and 6°C above and below that temperature. This allowed the determination of the true or continuous low temperature grade for each binder based on stiffness and m-value criterion separately. Finally, all BBR tests were performed twice with a replicate sample to validate its repeatability. In total, two tests were performed and the average of the two was used for further analysis. Figure 2.12 and Figure 2.13 display typical results for the stiffness and m-value versus temperature, respectively.

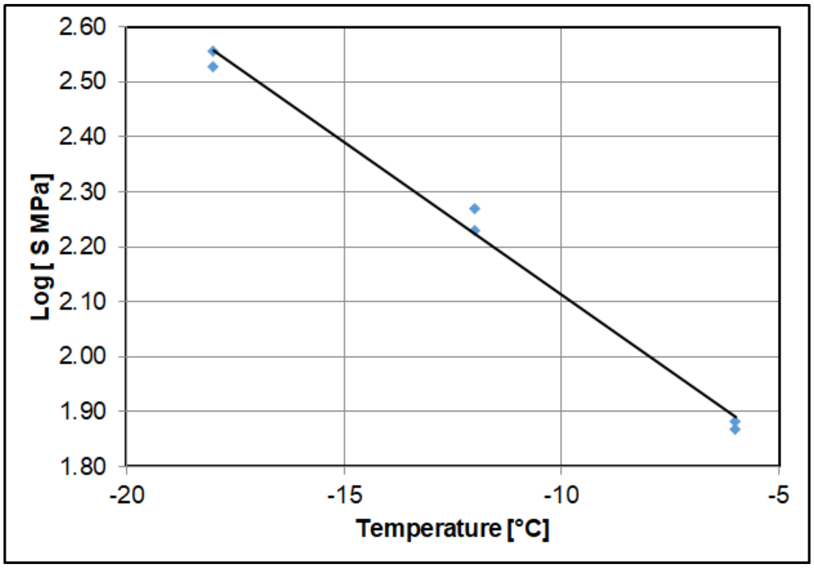

Figure 2.12. Typical graph of Stiffness (S) versus temperature

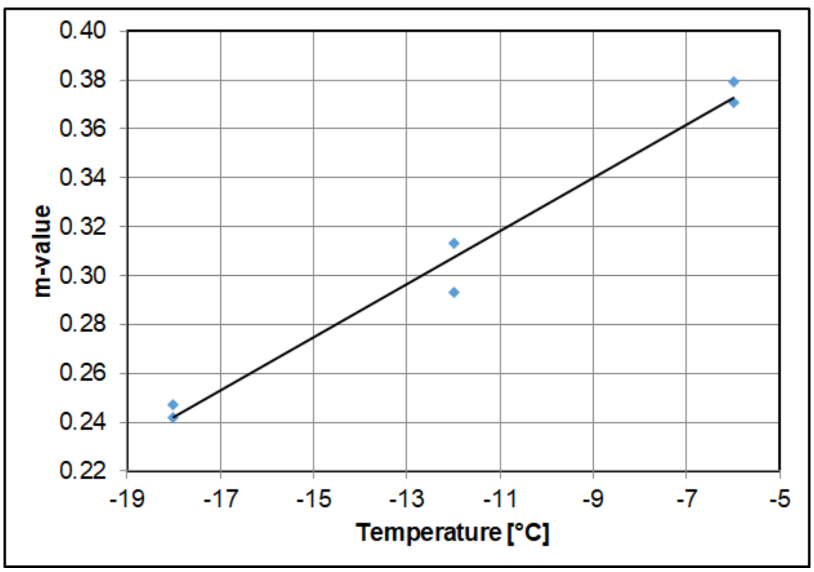

Figure 2.13. Typical graph of m-value versus temperature

2.6 MIXTURE TESTING

2.6.1 Overview

Conventional TxDOT laboratory mixture tests and other mixture tests were performed to evaluate the performance of mixtures in this study. This included mixtures with the original specified binder, mixtures with the substitute binder, as well as mixtures with and without RAP. The Hamburg Wheel Tracking Device was used to assess the rutting resistance and moisture susceptibility of asphalt mixtures. An electro-hydraulic testing machine with a function generator capable of producing the desired wave form of force was used to perform the Overlay Test (OT), creep-recovery test and the resilient modulus test on mixtures. The results from the OT were used to assess the fatigue resistance of mixtures. While the resilient modulus and creep-recovery tests both provided elastic recovery characteristic of mixtures. Lastly, the Indirect Tensile Strength Test (IDT) was performed on mixture specimens to determine tensile strength, however, unlike the current test procedure that requires the total load at failure and indirect tensile strength, for this study, both the total load at failure and the total deformation at failure were recorded.

2.6.2 Specimen fabrication

All materials used in this study such as aggregate, RAP, and binder were obtained from asphalt production plants within the state of Texas. The Job Mix Formula (JMF) that included RAP were exclusively considered and selected.

Test specimens were fabricated following procedures associated with each test method. All mixtures specimens were compacted using the Superpave Gyratory Compactor (SGC) according to the procedure specified in Tex-241-F (2015) with a diameter of 5.9 in. and varying heights depending on the test to be performed. The temperature of the material during mixing and compaction was controlled following Table 2.2 from Tex-241-F (2015).

Table 2.2. Mixing and compaction temperatures in TxDOT Specification Tex-241-F (2015)

Binder PG Grade	Mixing Temperature, °F (°C)	Compaction Temperature, °F (°C)
64-22	290 (143)	250 (121)
64-28	300 (149)	275 (135)
70-22	300 (149)	275 (135)
70-28	325 (163)	300 (149)
76-16	325 (163)	300 (149)
76-22	325 (163)	300 (149)

Then, using the saw as shown in Figure **??**, the specimens were cut to the specified dimensions following the specification Tex-242-F (2014) for HWT test, and Tex-248-F (2017) for OT.

Figure 2.14. Metal wet saw used to prepare mixture specimen

2.6.3 Gradation

The gradation for the original mixes were specified in the JMF and compacted following the gradation of each bin and binder content. One of the objectives of this study was to evaluate the effect of higher RAP content in a mix when 10% additional RAP than originally specified in the JMF was used. Also, mixtures without RAP were fabricated and tested to serve as a baseline for comparison. For mixes that contained a different percentage of RAP compared to the JMF, appropriate adjustments were made to the percentages of different aggregates so that the final gradation of all mixes were almost the same. Similar to the binder testing table, specimens with different percentages of RAP were fabricated to study the influence of RAP inclusion in asphalt mixtures. The following list of testing categories of mixtures with combination of RAP were created:

There were two different types of mixes without RAP. First, with the virgin binder originally specified for the job. Second, with virgin binder substituted for the job when RAP was included in the mix. As a result, a total of four different mixtures were evaluated per section. The list of different mixes can be observed as follows:

- Specified virgin binder + virgin aggregate (representing a mixture with performance expected from the engineers).
- Substitute virgin binder + virgin aggregate (representing the baseline mixture with binder that was actually used with no RAP).

- Substitute virgin binder + virgin aggregate + RAP as JMF (representing a mixture with performance similar to the mixture that was actually constructed).
- Substitute virgin binder + virgin aggregate + RAP as JMF +10% additional RAP (representing a mixture with higher percentage of RAP in a hypothetical case with high RBR).

This study evaluated materials from two different geographical locations within the state of Texas. The two selected locations are referenced to a District 1 and District 2. For District 1, the individual bins included Grade 4, W.C.F, Cyclone Sand, Grade 6, Grade -6, Lime, Fractionated Recycled Asphalt Pavement (RAP), and Recycled Asphalt Shingles (RAS). The difference in the proportion of each bin for different asphalt mixtures developed for this study can be observed in Figure 2.15. For asphalt mixtures without RAP, the proportion of other bins was increased and vice-versa for mixtures with 10% additional RAP. The individual bins were altered to minimize the difference in the final gradation for mixes, which can be observed in Figure 2.16

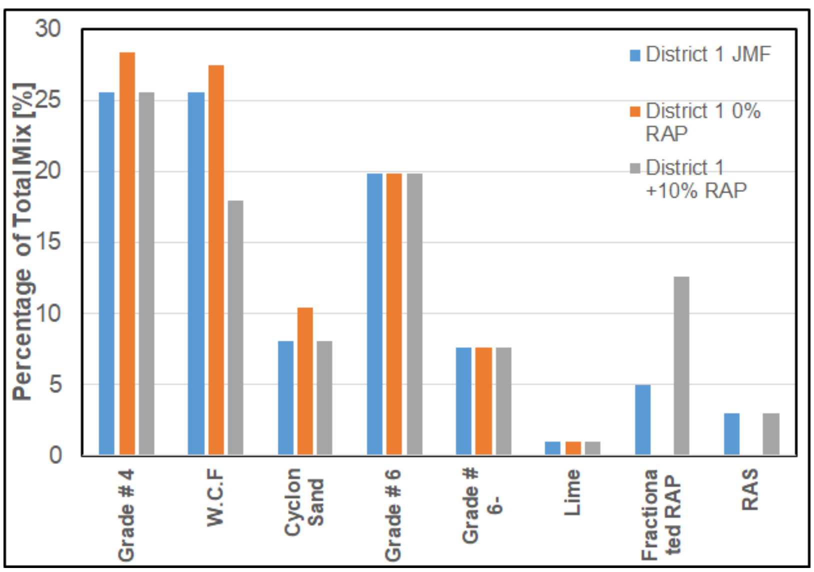

Figure 2.15. Differences in the proportion of each bin for different RAP mixes in District 1

For District 2, individual bins included D-Rock, Shot Rock, Screening 4, Lime, Fine RAP, and Coarse RAP. The design process of the mixes for District 2 was exactly the same as the design process for District 1. The change in the amount of RAP was compensated

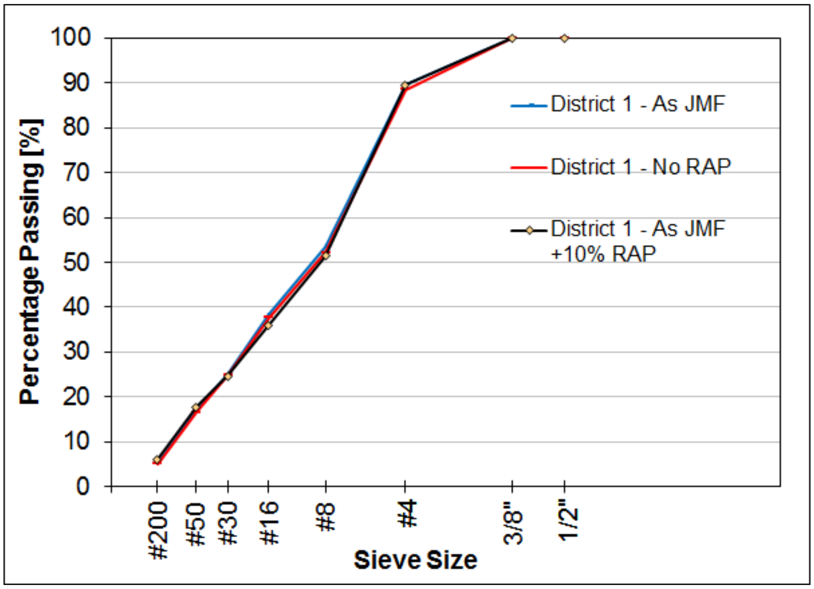

Figure 2.16. Differences in the final gradation for different mixes in District 1

for by changing other bins within the JMF. The difference in the proportion of each bin for different RAP mixes can be observed in Figure 2.17. Also, individual bins were changed to minimize the difference in the final gradation for different mixes, which can be observed in Figure 2.18.

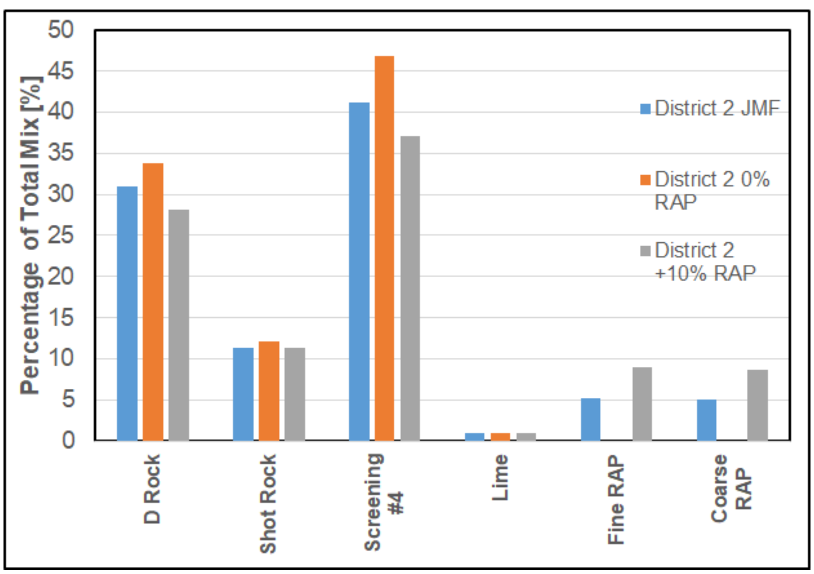

Figure 2.17. Differences in the proportion of each bin for different RAP mixes in District 2

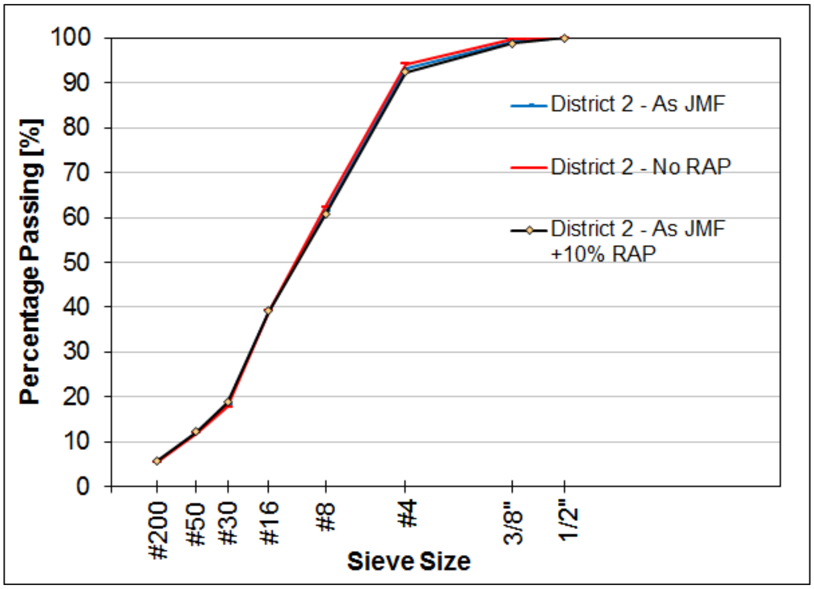

Figure 2.18. Differences in the final gradation for different mixes in District 2

Figures 2.15 and 2.17 illustrates the adjustments made to the different aggregate sources when no RAP or 10% additional RAP was used so that the final gradation was similar to the JMF. In District 1, the amount of RAS included in the mixes was kept constant for JMF and 10% additional mix because the focus of the study was on the effect of RAP on the performance of asphalt mixtures.

2.7 HAMBURG WHEEL TRACKING TEST

The Hamburg Wheel Tracking Device (HWTD) was used to evaluate the susceptibility of the asphalt mixture to rutting and moisture induced damage of a mixture. The procedure for Tex-242-F (2014) was followed for the test. A load of 159 lb is applied to the specimen via a steel wheel that travels back and forth over the sample at a constant rate of 50 passes per minute. Following the procedure, the test was performed under water at a constant temperature of 50°C and the rut depth was recorded after every 100 passes of the wheel with a maximum rut dept of 12.5 mm or 20,000 passes as the termination criteria. Total of four individual samples were used per test as seen in Figure 2.19. Two sets of two samples were cut and put together to simulate a slab and the other set of two specimens were replicates of the first two specimens to check the repeatability.

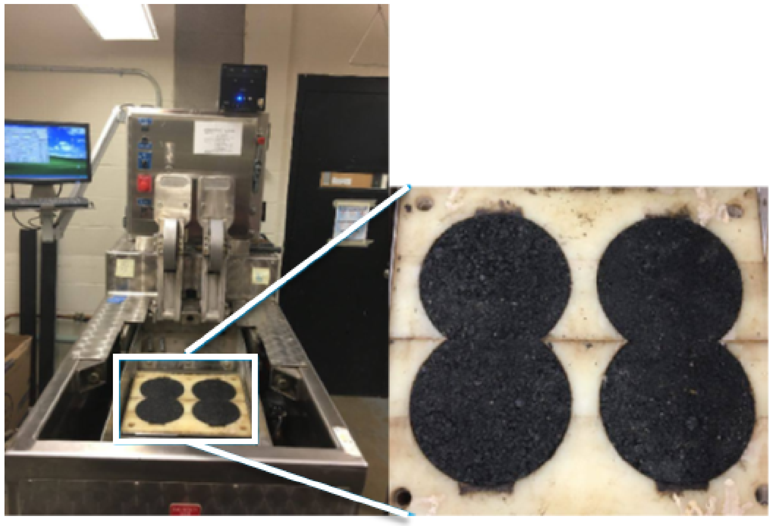

Figure 2.19. Hamburg wheel tracking device with samples loaded

2.8 OVERLAY TEST

An electro-hydraulic testing machine was utilized to perform the Overlay Test (OT) to evaluate the susceptibility of asphalt mixtures to fatigue cracking . The specific model used for this study was Instron 8372. The procedure in Tex-248F (2017) was followed to conduct the test. A displacement controlled tensile load was applied following a cyclic triangular waveform with a constant maximum displacement of 0.025 in (0.06 cm). After the maximum displacement was reached, it returns to its initial position in 10 seconds, counting as one cycle. No rest period was allowed between cycles.

For the overlay test, the following parameters were measured and calculated:

- maximum load,
- fracture area (the area under the load verses displacement curve until the maximum load),
- fracture energy (the energy required to initiate a crack on the bottom of the specimen at the first loading cycle calculated using Equation 2.15),
- crack resistance index, (the reduction in load required to propagate cracking under the cyclic loading condition of the OT), and

- number of cycles to failure.

$$G_c = W_c/b * h \tag{2.15}$$

For the OT, the specimen prepared earlier was mounted on metal plates using an epoxy resin (specified in the Tex-248F) to ensure proper adhesion between the sample face and the steel plates. Specification Tex-248-F (2017) suggests 8 hours of curing time for sufficient bonding strength.

2.8.1 Summary

For the purpose of this study, JMF from two different districts, District 1 and District 2, were evaluated to obtain the characteristic of the binder and performance of mixtures with varying amount of recycled material. For all the tests, two specimens were tested (replicate) to validate the repeatability and to ensure the result was not an outlier. In order to characterize the binders with varying amount of recycled binder, following tests were performed:

- Short time sweep test (using the DSR)
- Muttiple Stress Creep and Recovery (MSCR) test (using the DSR)
- Frequency sweep test (using the DSR)
- Flexural creep stiffness (using the BBR)

For mixtures, following tests were performed to evaluate its performance:

- Hamburg wheel tracking test
- Overlay test

For both binder and mixture testing, following variation of materials were tested:

- Specified Binder
- Substitute Binder
- Substitute Binder + RAP as JMF
- Substitute Binder + RAP as JMF + 10% additional RAP

CHAPTER 3. EVALUATION OF ASPHALT BINDERS AND ASPHALT MIXTURES

3.1 OVERVIEW

This chapter provides an overview of the performance of the asphalt binders and mixtures with various Recycled Binder Ratios (RBRs), different combinations of virgin binder, and recycled binder. For each of the two locations, the following variations of binders were evaluated.

- Specified binder
- Substitute binder
- Substitute binder + recycled binder as specified in JMF
- Substitute binder + recycled binder as specified in JMF +10% additional recycled binder

Note that the recycled binder was recovered from a RAP sample corresponding to the specific location. Similar to the binders, for each of the two sections, the following combinations of the mixture were evaluated.

- Specified binder with virgin aggregates
- Substitute binder with virgin aggregates
- Substitute binder + RAP as specified in JMF
- Substitute binder + RAP as specified in JMF +10% additional RAP

Note that the change in ratio of the RAP binder to total binder affects the gradation of the mixture because the gradation of RAP is different from the final gradation of the JMF. The ratio of all the bins in the JMF were adjusted such that gradation for all four testing categories was similar to the JMF with RAP. The final gradation for all the specimens are detailed in Chapter 2. The first two categories of materials listed above (specified binder and substitute binder) were included to serve as controls without any recycled material. The specified binder represents the original binder specified for the job and the rheological properties of the specified binder represents the performance of the binder expected for job. The substitute binder was the baseline virgin binder containing no recycled binder representing the original binder that must be modified with recycled material to perform similarly to specified binder. By establishing this baseline, the study can clearly observe the effect of mixing recycled binder with virgin binder. The third category of specimen, i.e. substitute virgin binder with recycled binder as specified in JMF, represents the material that was ultimately used for the job. The fourth category of specimen, i.e. substitute binder with virgin aggregates plus recycled binder as specified in JMF +10% additional recycled binder, was created for this study to observe the characteristics of binder containing high ratio of recycled binder to virgin binder.

3.2 JOB MIX FORMULA

The two JMF selected for this study were from different climatic regions within the State of Texas. Figure 3.1 shows the different climatic zones within Texas. Zone 3 where District 1 is located is the dry-cold region while Zone 4 where District 2 is located is the dry-warm region.

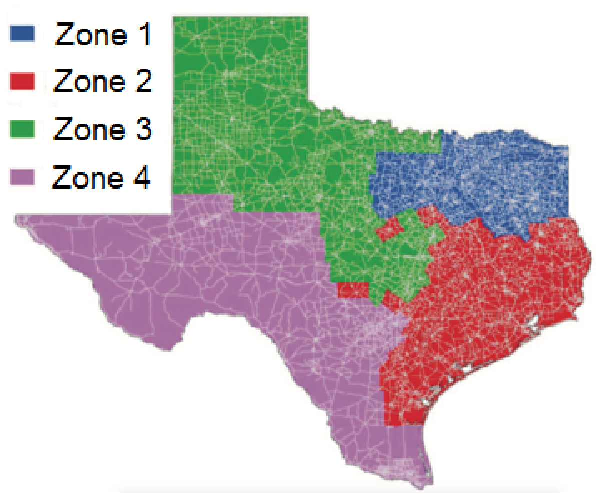

Figure 3.1. Typical climatic regions in the State of Texas; wet-cold (Zone 1), wet-warm (Zone 2), dry-cold (Zone 3), and dry-warm (Zone 4)

The JMF, virgin binder, recycled material, aggregates, and additives used for both districts were obtained to fabricate the samples according to the testing matrix.

3.2.1 District 1

District 1 is located in the southern region of Texas that is categorized as a dry-warm climatic region. The JMF included total of 8 different bins that included "Grade 4", "W.C.F", "Cyclone Sand", "Grade 6", "Grade -6", "Lime" for the aggregate bin fractions and "Fractionated RAP", and "RAS" for the recycled material bin fractions. The Grade 6 and Grade-6 were delivered as one bin so the percentages of the two bins were not changed for different RBR ratio. Also the quantity of RAS was kept constant as we increased the RBR for additional 10%, because the purpose of this study was to observe the effect of increasing RAP quantity. Table 3.1 shows the JMF for the District 1.

Table 3.1. JMF for District 1 - Optimum binder content of 5.4%

	Bin No.1 Grade # 4	Bin No.2 W.C.F	Bin No.3 Cyclon Sand	Bin No.4 Grade # 6	Bin No.5 Grade # 6-	Bin No.6 Lime	Bin No.8 Fractionated RAP	Bin No.9 RAS	Final Gradation
Individual Bin, %	27.0	27.0	8.5	21.0	8.0	1.0	7.0% of Binder 4.9% of Tot. Agg. 5.0% of Tot. Mix	17.5% of Binder 2.6% of Tot. Agg. 3.0% of Tot. Mix	
Sieve Size	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing
3/4"	100	100	100	100	100	100	100	100	100.0
1/2"	100	100	100	100	100	100	100	100	100.0
3/8"	62.2	99.8	99.8	99.8	100	100	99.2	100	89.6
No. 4	8.7	97.6	99.2	22.3	58.4	100	70.5	99.8	53.5
No. 8	7	78.4	98.2	2.2	6.9	100	49.7	96.7	38.4
No. 30	5.1	38.1	96.7	1.6	3.8	100	33.5	72.9	25.1
No. 50	4.4	23.1	63.3	1.5	3.3	100	28.3	61.1	17.4
No. 200	1.7	4.2	18.3	0.9	1.6	100	12.3	15.2	5.5

3.2.2 District 2

District 2 located in the northern region of Texas, categorized as dry-cold climatic region. The JMF included total of 8 different bins that included "D-Rock", "Shot Rock", "Screening 4", and "Lime" for the aggregate bin fractions and "Fine RAP", and "Coarse RAP" for the recycled material bin fractions. Table 3.2 shows the JMF for the District 2.

3.3 EVALUATION OF ASPHALT BINDER

3.3.1 Rutting resistance of binder

3.3.1.1 Superpave criteria

The Superpave criteria specifies two parameters to characterize the binder's ability resist rutting: the complex shear modulus ($|G^*|$), representing the stiffness of the binder,

Table 3.2. JMF for District 2 - Optimum binder content of 6.3%

	Bin No.1 D' Rock	Bin No.2 Shot Rock	Bin No.3 Screenings #4	Bin No.4 Lime	Bin No.8 Fine RAP	Bin No.9 Coarse RAP	Final Gradation
Individual Bin, %	33.0	12.0	44.0	1.0	9.9% of Binder 5.0% of Tot. Agg. 5.2% of Tot. Mix	6.8% of Binder 5.0% of Tot. Agg. 5.0% of Tot. Mix	
Sieve Size	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing	Cum. % Passing
3/4"	100	100	100	100	100	100	100.0
1/2"	99.5	99.5	100	100	100	89.7	99.3
3/8"	84.3	99.0	100	100	94.3	73.7	93.1
No. 4	19.7	60.5	92.7	100	76.8	36.8	61.2
No. 8	3.5	20.0	68.7	100	62.5	25.2	39.2
No. 30	1.3	3.6	31.8	100	34.4	16.9	18.4
No. 50	1.0	2.3	20.5	100	17.8	11.9	12.1
No. 200	0.5	1.3	8.3	100	11.0	3.0	5.7

and the phase angle (δ), representing the viscoelastic nature of the binder. In order to resist rutting, a binder should be stiff and elastic, meaning stiffness and elasticity are directly proportional to resistance to rutting. Therefore, parameter $G^*/\sin\delta$ will be greater when G^* is maximized and $\sin\delta$ is minimized.

The two parameters were obtained by performing a short time sweep test at 3 different temperatures. The testing temperatures were dependent on the high grade of the binder because the three temperatures were the PG high grade and 6°C above and below that grade temperature. With the measured results, the continuous high grade was interpolated using a linear relationship between $(G^*/\sin\delta)$ over temperature. The minimum $G^*/\sin\delta$ requirement for unaged binder is 1.0 kPa and for RTFO aged binder is 2.2 kPa under Superpave design criteria.

Table 3.3 shows the true high grade of District 1 for both unaged and RTFO aged binders based on $G^*/\sin\delta$. Figure 3.2 shows the relationship between $Log(G^*/\sin\delta)$ versus temperature of unaged binders, and Figure 3.3 for RTFO aged binders .

Table 3.4 shows the true high grade of District 2 for both unaged and RTFO aged binder based on $G^*/sin\delta$. For the same District 2, Figure 3.4 shows the relationship between $Log(G^*/sin\delta)$ versus temperature of unaged binders and, Figure 3.5 for RTFO aged binders.

Based on the testing results of $G^*/\sin\delta$ parameter for the two districts, the following conclusions can be drawn. Assuming that $G^*/\sin\delta$ parameter is an accurate indicator of rutting, in both districts, as expected, higher rutting resistance can be observed in specified binder and substitute binder blended with recycled binder from RAP compared to

Table 3.3. True high performance grade for District 1

Asphalt Binder Material	True High Grade Temperature Unaged, °C	True High Grade Temperature RTFO Aged, °C
Specified PG76-22	79.3	78.7
Substitute PG64-22	71.6	70.1
Substitute PG64-22 +RAP as JMF	81.0	80.9
Substitute PG64-22 +RAP as JMF +10%	83.2	84.1

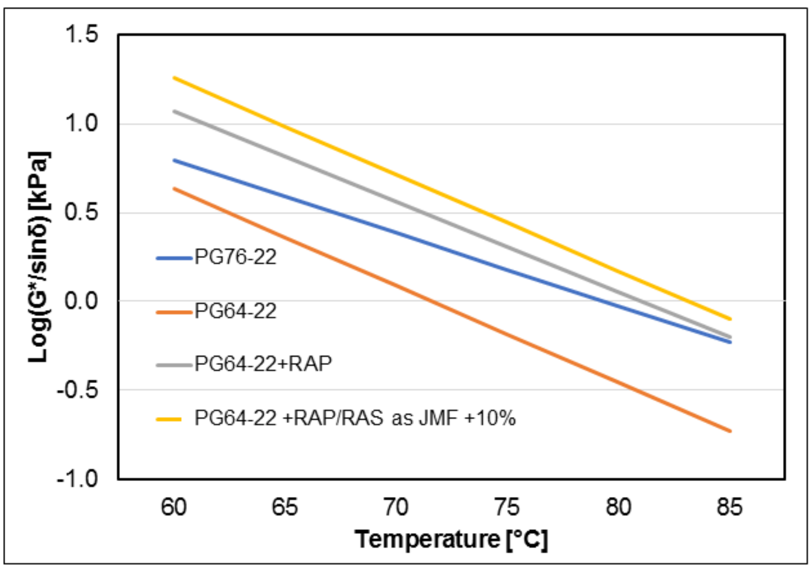

Figure 3.2. District 1 unaged binders $(G^*/\sin\delta)$ versus temperature

binder with just the substitute binder. For District 1, an increase in stiffness with an increases in the amount of recycled binder was evident. In District 2, the stiffness of the binder increased from substitute binder to substitute binder + recycled binder as used in JMF but the stiffness decreased by 0.9 °C when 10% additional RAP was added to the substitute binder. The decrease of 0.9 °C is possibly within the margin of error to conclude

Table 3.4. True high performance grade for District 2

Asphalt Binder Material	True High Grade Temperature Unaged, °C	True High Grade Temperature RTFO Aged, °C
Specified PG76-28	79.8	78.6
Substitute PG70-28	76.1	74.8
Substitute PG70-28 +RAP as JMF	79.4	78.1
Substitute PG70-28 +RAP as JMF +10%	77.4	77.2

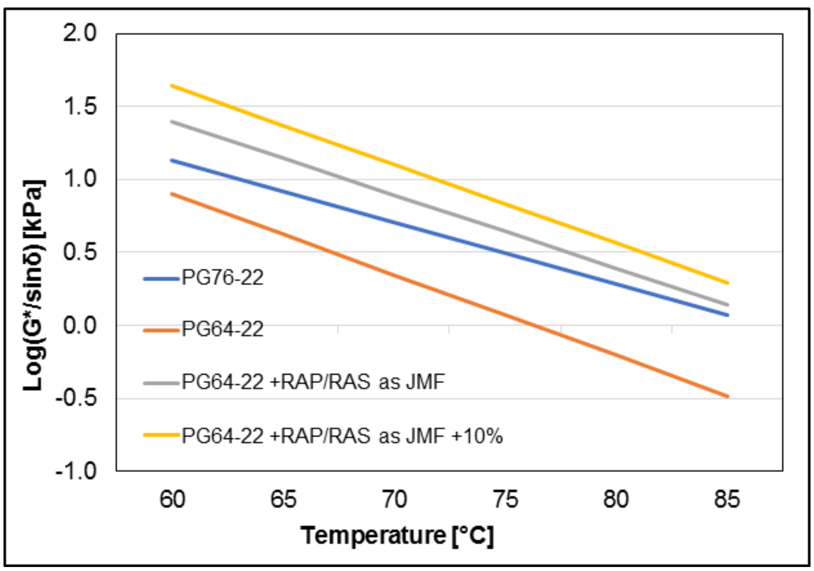

Figure 3.3. District 1 RTFO aged binders $(G^{*}/\sin\delta)$ **versus temperature**

that there was an increase in high grade when recycled binder from RAP was added. The true high grade value of the specified binder was very similar to the true high grade value of the substitute binder + recycled binder as used in the JMF for both districts.

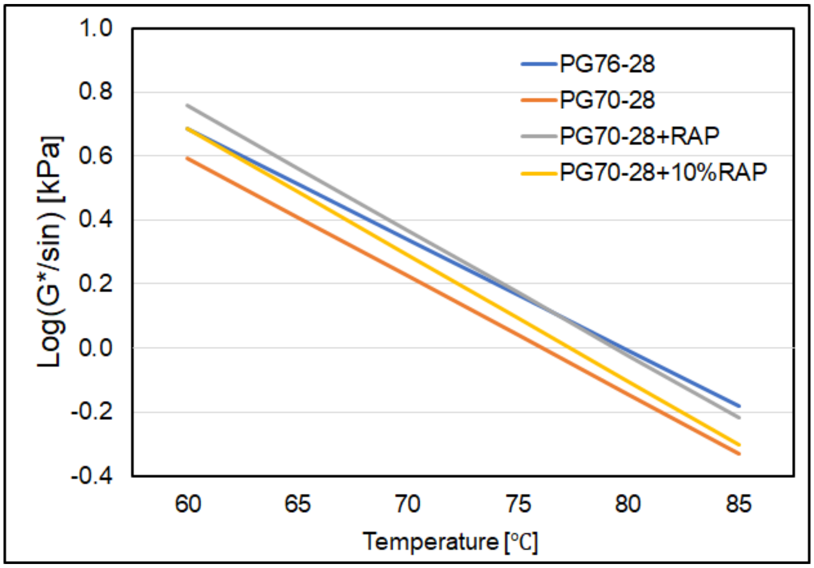

Figure 3.4. District 2 unaged binders $(G^*/\sin\delta)$ versus temperature

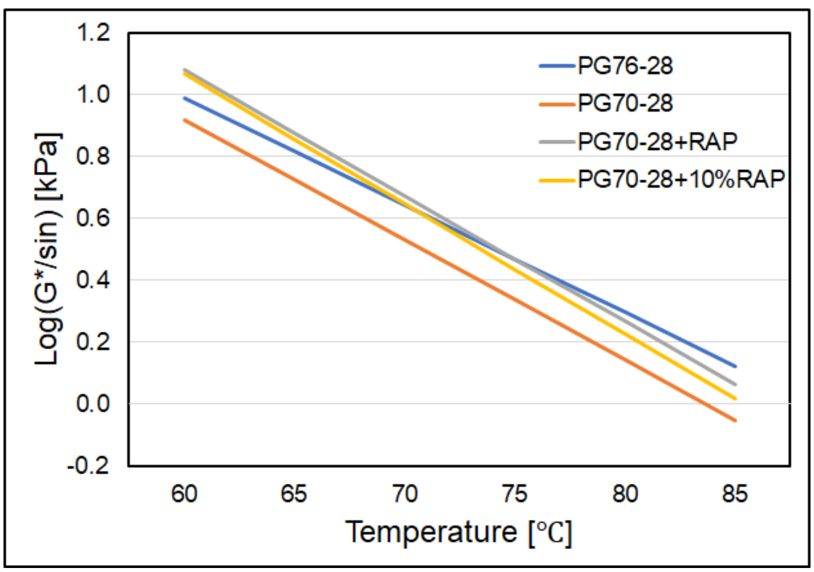

Figure 3.5. District 2 RTFO aged binders $(G^*/\sin\delta)$ versus temperature

3.3.1.2 Multiple stress creep and recovery (MSCR) test

In addition to the short time sweep test to obtain the complex shear modulus and phase angle, the Multiple Stress Creep and Recovery (MSCR) test was performed to further evaluate the binder's ability to resist rutting. The MSCR test was designed to better represent the binder's ability to resist permanent deformation. The MSCR test was performed

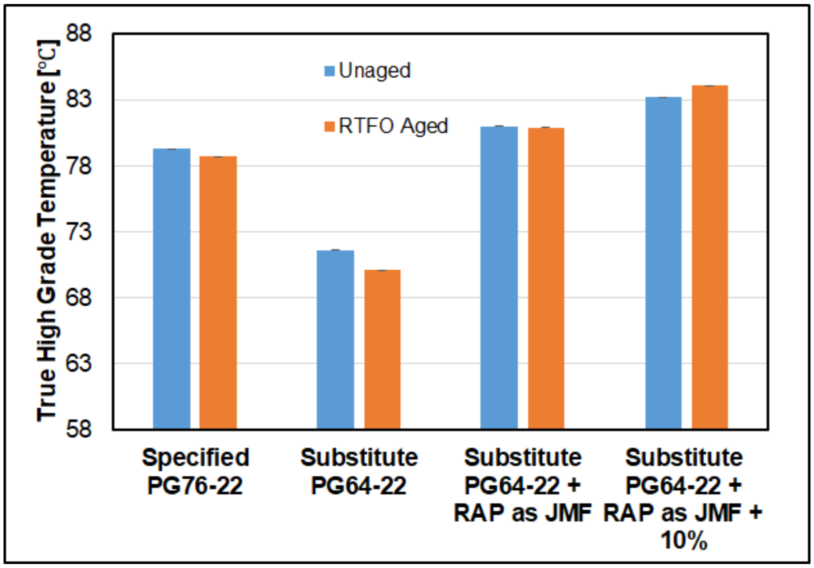

Figure 3.6. Summary of District 1 true high grade

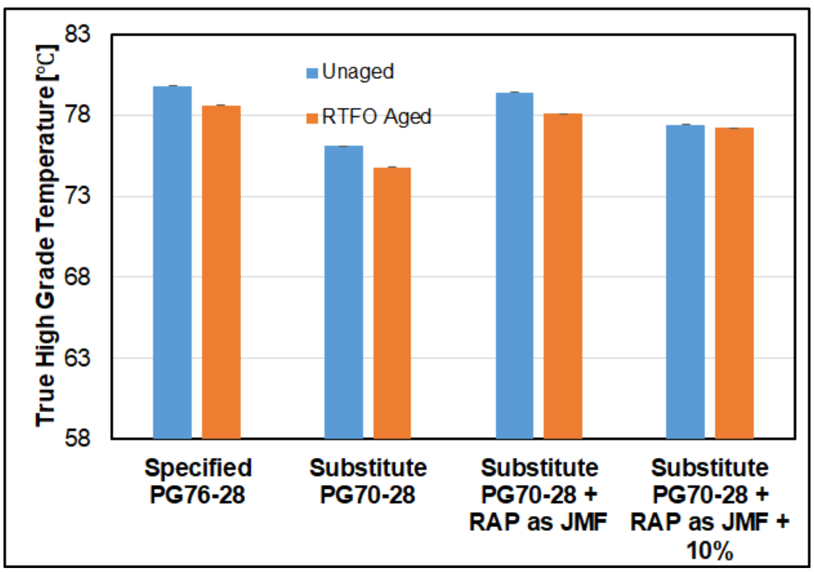

Figure 3.7. Summary of District 2 true high grade

following the ASTM D7405 (2015) standard using RTFO aged binders.

For the MSCR test, two parameters, percent recovery (R%) and the non-recoverable creep compliance (J_{nr}), were obtained. The percent recovery is a measure of the deformation recovered during the rest period in each cycle compared to the total strain occurred when a constant stress is applied. In other words, it is the difference between the adjusted strain at the end of creep and the adjusted strain at the end of recovery. The percent recovery is intended to provide a means to determine the presence of elastic response in asphalt binders. The non-recoverable creep compliance is the relationship between the adjusted strain at the end of recovery and the stress applied. Figure 3.8 and 3.9 illustrates the MSCR results for all binder from District 1 and District 2, respectively. Table 3.5 and 3.6 shows the summary of R%, and J_{nr} at 100 and 3200 Pa stress applied for District 1 and District 2, respectively.

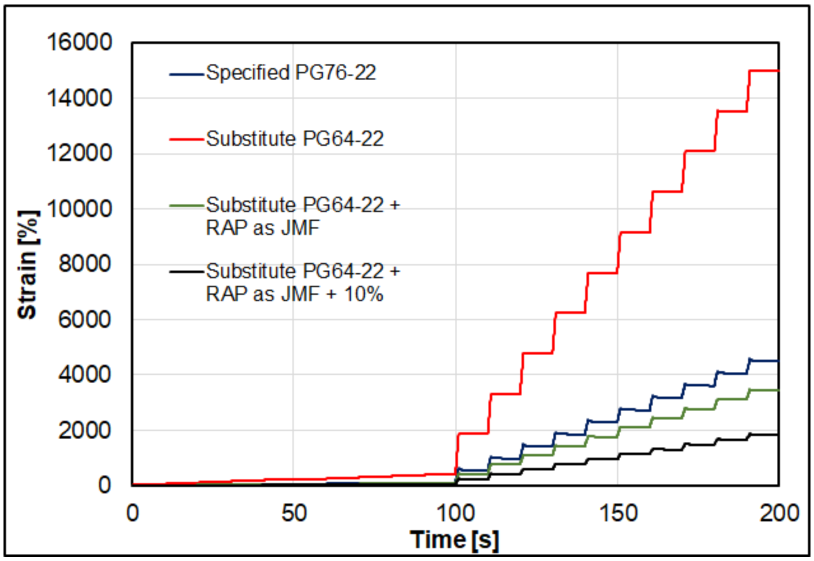

Figure 3.8. MSCR results for District 1 at 70°C

Table 3.5. Percentage recovery and non-recoverable creep compliance at 100 and 3200 Pa stress applied for District 1

Asphalt Binder Material	$R\%_{100}$ %	$J_{nr,100}$, $1/kPa^{-1}$	$R\%_{3200}$ %	$J_{nr,3200}$, $1/kPa^{-1}$
Specified PG76-22	31.8	1.0	15.8	1.4
Substitute PG64-22	2.6	4.1	0.6	4.6
Substitute PG64-22 +RAP/RAS as JMF	14.9	0.9	7.0	1.0
Substitute PG64-22 +RAP/RAS as JMF +10%	21.6	0.5	14.0	0.6

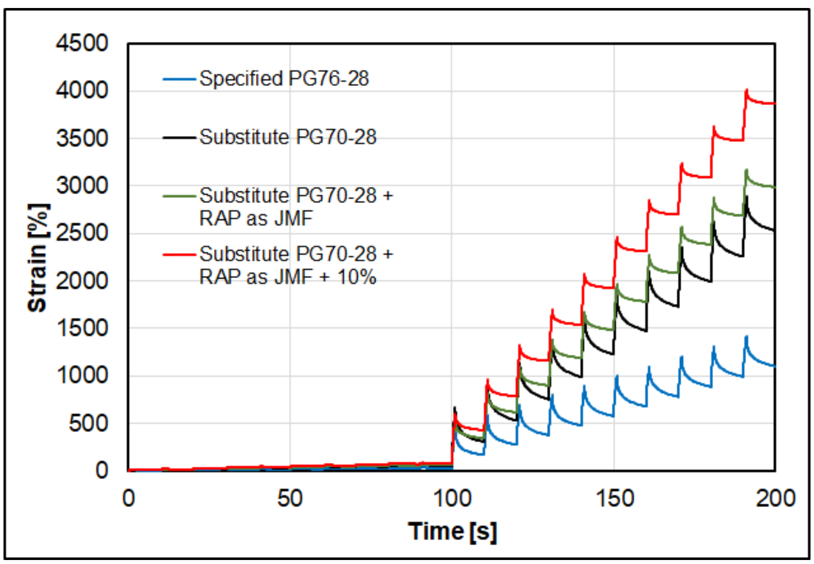

Figure 3.9. MSCR results for District 2 at 70°C

The creep and recovery cycles with 100 Pa applied stress is not representative in the Figures 3.8 and 3.9 because the strain from 3200 Pa is relatively higher. Figures 3.10 and 3.11 show a detailed illustration of the first cycle of MSCR at 100 Pa stress level for

Table 3.6. Percentage recovery and non-recoverable creep compliance at 100 and 3200 Pa stress applied for District 2

Asphalt Binder Material	R, 100 %	Jnr, 100 $1/kPa^{-1}$	R, 3200 %	Jnr, 3200 $1/kPa^{-1}$
Specified PG76-28	77.3	0.3	74.1	0.3
Substitute PG70-28	69.7	0.6	59.8	0.8
Substitute PG70-28 +RAP as JMF	54.2	0.7	39.5	0.9
Substitute PG70-28 +RAP as JMF +10%	47.9	0.8	29.6	1.2

District 1 and District 2, respectively.

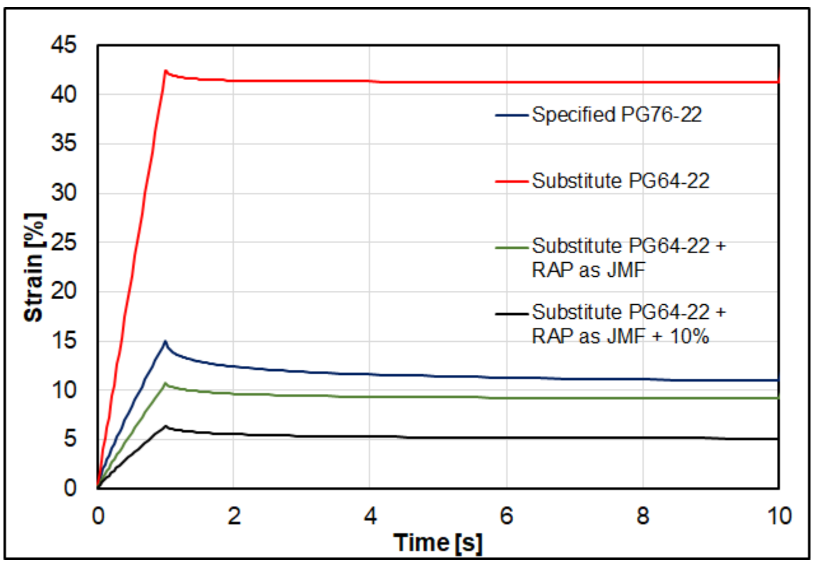

Figure 3.10. District 1 first cycle of MSCR with 100 Pa applied at 70°C

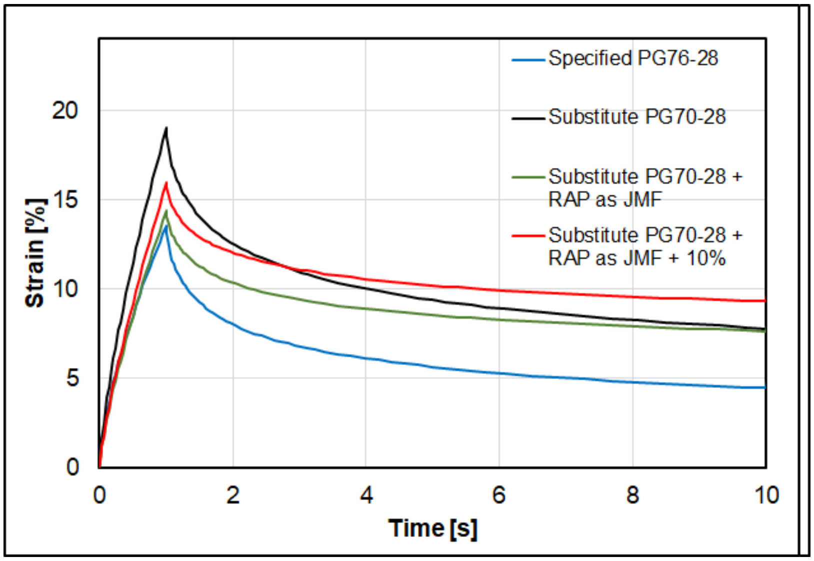

Figure 3.11. District 2 first cycle of MSCR with 100 Pa applied at $70°$**C**

Based on the results from the MSCR testing, following conclusions can be drawn. For both districts, the percent recovery (both $R_{0.1}$ and $R_{3.2}$) and the non-recoverable creep compliance for substitute binder decreased and increased, respectively, compared to that of the specified binder. In district 2, as expected from adding recycled binder, the percent recovery decreased and the non-recoverable creep compliance increased. But in District 1, the percent recovery increased and the non-recoverable creep compliance decreased as recycled binder was added to the substitute binder indicating higher elastic response to stress applied with addition of recycled binder from RAP. The recovered strain increased by 45% and 25% for 100 Pa applied stress and increased by 199% and 248% for 3200 Pa applied stress when comparing the substitute binder (PG64-22) to substitute binder combined with the recycled binder as specified in the JMF, and to substitute binder with 10% additional recycled binder, respectively.

3.3.2 Fatigue cracking

Glover-Rowe (G-R) parameter was computed using the master curve for a binder to understand the binder's resistance to cracking. Tables 3.7 and 3.8 summarize the complex modulus and phase angle at 15°C and at 0.005 rad/s, and the G-R parameter for District 1, and District 2, respectively.

Figures 3.12 and 3.13 compare the complex modulus and G-R parameter of different binder variations for District 1 and District 2, respectively. In both districts, as recycled binder was added to substitute binder, the G-R parameter and the complex modulus increased indicating a reduced resistance to cracking. In district 1, the G-R parameter was higher for specified binder (PG76-22) compared to substitute binder (PG 64-22) indicating worse cracking resistance for the PG76-22 binder. This may be attributed to the procedure of G-R test, which specify all types of binders to be tested at 15 °C, without accounting for the binder's high grade.

Table 3.7. Complex modulus, phase angle, and Glover-Rowe parameter at 15°C, and 0.005 rad/s for District 1

Asphalt Binder Material	Complex Modulus G*, kPa	Phase Angle δ, rad	Glover-Rowe Parameter, kPa
Specified PG76-22	290.6	0.97	112.5
Substitute PG64-22	260.9	1.05	73.8
Substitute PG64-22 +RAP/RAS as JMF	658.3	0.89	336.0
Substitute PG64-22 +RAP/RAS as JMF +10%	700.5	0.86	388.9

Table 3.8. Complex modulus, phase angle, and Glover-Rowe parameter at 15°C, and 0.005 rad/s for District 2

Asphalt Binder Material	Complex Modulus G*, kPa	Phase Angle δ, rad	Glover-Rowe Parameter, kPa
Specified PG76-28	80.1	0.97	31.5
Substitute PG70-28	144.6	0.96	58.1
Substitute PG70-28 +RAP as JMF	193.1	0.96	78.9
Substitute PG70-28 +RAP as JMF +10%	233.8	0.96	94.0

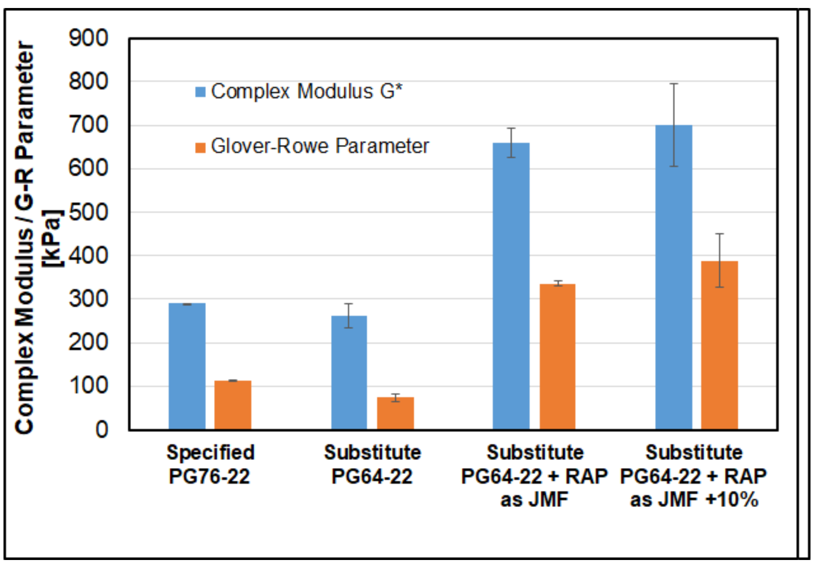

Figure 3.12. District 1 summary of Glover-Rowe tests

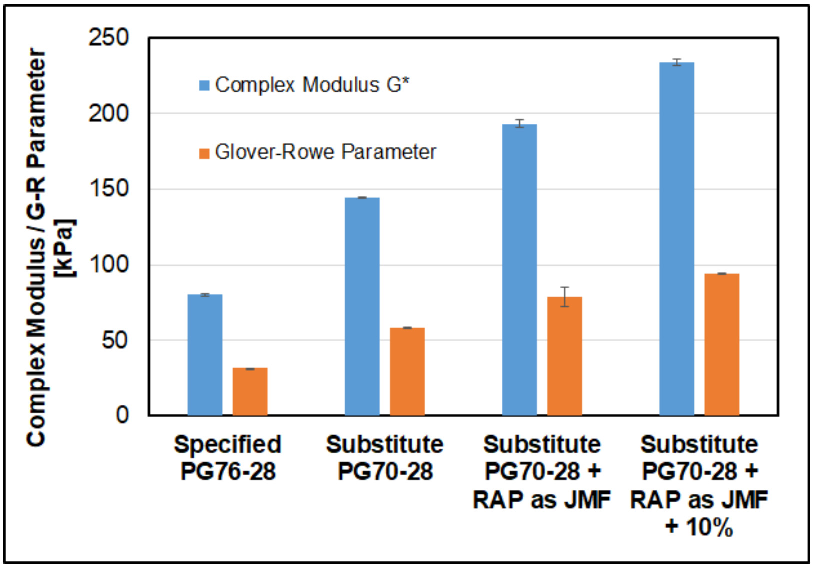

Figure 3.13. District 2 summary of Glover-Rowe tests

3.3.3 Thermal and fatigue cracking resistance of asphalt binder

To measure the low cracking resistance of the binders in this study, the Bending Beam Rheometer (BBR) equipment was used to measure the creep stiffness (S) and m-value. Current Superpave criteria requires a maximum S of 300 MPa and a minimum m-value of 0.300 for PAV aged binders. The BBR testing was performed on PAV aged asphalt binders. The susceptibility to thermal cracking increases with age of the pavement, which explains the rational for testing only PAV aged binders.

Tables 3.9 and 3.10, and Figures 3.14 and 3.15 summarize the results for BBR testing for District 1 and District 2, respectively. Tables 3.9 and 3.10 include the results for the temperature satisfying the requirement for S and m-value, low PG grade from the two temperatures, and ΔT_c, which is the difference between the two true low temperatures.

From the results for both districts, as expected, higher low temperature grade can be observed as recycled binder is added. Also, ΔT_c increased as binder from RAP was added. In District 2, the ΔT_c parameter increased from substitute binder with no recycled binder to substitute binder with recycled binder as specified in the JMF but, unlike District 1, ΔT_c parameter decreased by 0.7 °C when 10% additional recycled binder from RAP was added. This decrease was within the margin of error. In general, ΔT_c parameter increased as recycled binder from RAP was added. It is also important to note that the binder including RAP failed to meet the required low PG grade in both districts, even for binder including

RAP content as specified in the JMF.

Table 3.9. District 1 BBR test summary

Asphalt Binder Material	True Low Temperature Stiffness, °C	True Low Temperature m-value, °C	Low PG Temperature, °C	ΔT_c, °C
Specified PG76-22	-26.6	-22.7	-22	-3.9
Substitute PG64-22	-26.9	-23.8	-22	-3.1
Substitute PG64-22 +RAP/RAS as JMF	-24.0	-20.0	-16	-3.9
Substitute PG64-22 +RAP/RAS as JMF +10%	-24.0	-17.9	-16	-6.2

Table 3.10. District 2 BBR test summary

Asphalt Binder Material	True Low Temperature Stiffness, °C	True Low Temperature m-value, °C	Low PG Temperature, °C	ΔT_c, °C
Specified PG76-28	-31.1	-29.5	-28	-1.6
Substitute PG70-28	-32.3	-30.1	-28	-2.2
Substitute PG70-28 +RAP as JMF	-28.3	-24.4	-22	-3.9
Substitute PG70-28 +RAP as JMF +10%	-27.7	-24.5	-22	-3.2

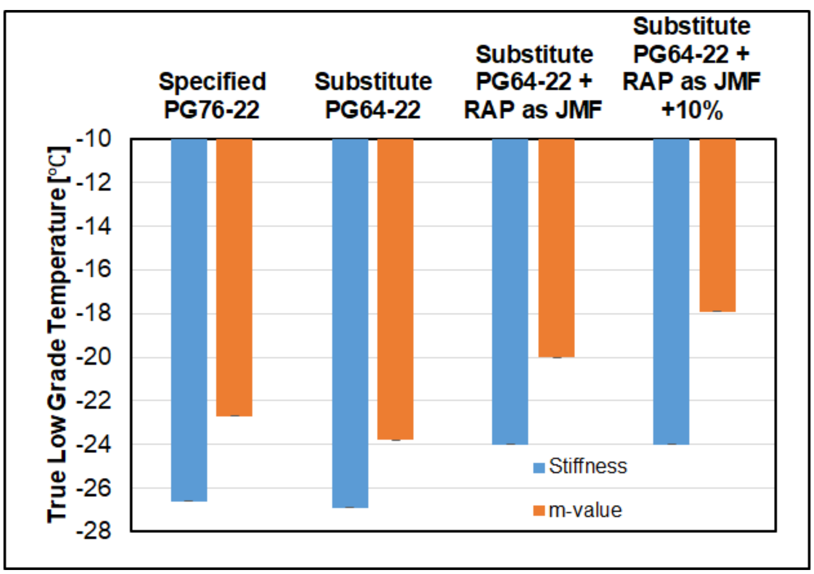

Figure 3.14. District 1 low PG grade based on stiffness and m-value

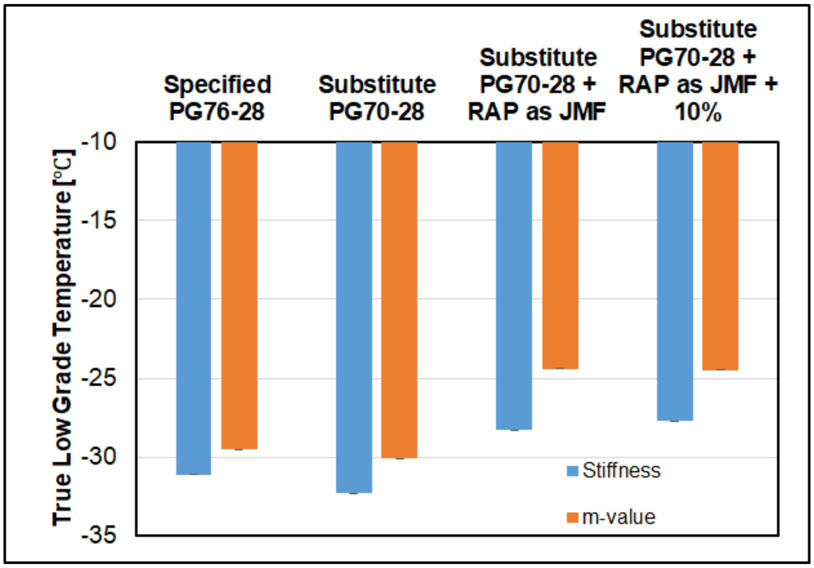

Figure 3.15. District 2 low PG grade based on stiffness and m-value

3.4 EVALUATION OF ASPHALT MIXTURE

3.4.1 Hamburg wheel tracking (HWT) test

Conventional TxDOT laboratory mixture tests were performed to validate the binder testing results. The HWT device was used to assess the rutting resistance and moisture damage resistance of full asphalt mixtures. The samples were prepared following the specification Tex-242-F (2014), and the test was performed according to the same specification. Two specimens were tested to validate consistency and for the final result the average of the two tests.

Figures 3.16 and Figure 3.17 present the results from this evaluation. All mixtures passed the number of wheel passes except for mixtures with substitute binder without RAP and specified binder without RAP in District 1. The stripping point for the mixture with substitute binder was at around 5,000 passes and for the mixture with specified binder was at around 15,000 passes. On the other hand, mixtures including same substitute binder but with RAP showed minimal rutting at 20,000 passes and no stripping point through the test. Note that the mixture with just the substitute binder was a hypothetical design intended to serve as a baseline and would not have been constructed in reality. So the failure of this mixture was not necessarily a cause for concern. The improved performance of the mixtures including RAP compared to the mixture with substitute binder without

RAP shows the enhancing properties of including RAP against rutting and stripping. The mixtures for District 2 illustrate high resistance to rutting. The individual performance of various mixtures in District 2 was not analyzed because the average rutting depth of all samples was minimal at around 3.5 mm.

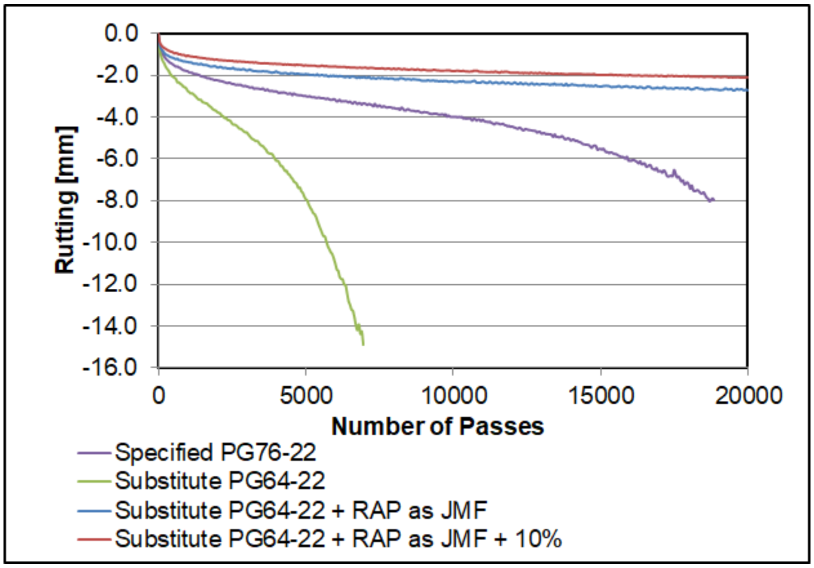

Figure 3.16. HWT results for District 1

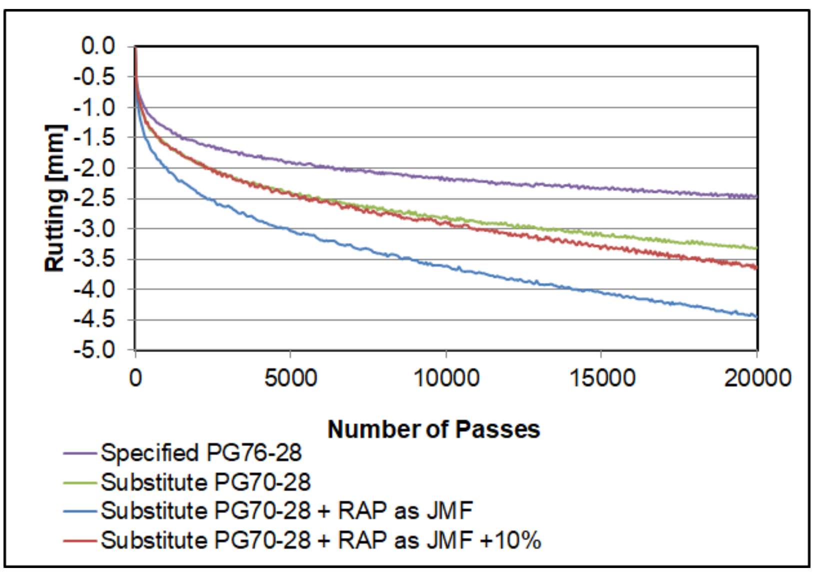

Figure 3.17. HWT results for District 2

3.4.2 Overlay test (OT)

The Overly Test (OT) was performed to investigate the ability for the mixture to resist fatigue cracking. The specimens for OT were prepared according to Tex-248-F (2017) specification, and the test was performed according to the same specification. The critical fracture energy and crack resistance index were obtained to characterize the asphalt mixture's resistance to cracking.

Tables 3.11 and 3.12 summarize the results from the OT for District 1, and District 2; respectively. Using Figures 3.18, 3.18, and 3.20 for District 1 and Figures 3.21, 3.22, and 3.23 for District 2, no trend or sensitivity to variations of mixtures was evident.

Table 3.11. Overlay test results for District 1

Asphalt Mixture Material	Max Load, lb	Fracture area, lb-in	Fracture Energy, lb-in/in^2	Number of Cycles to Failure	Crack Resistance Index, β
Specified PG76-22	951.6	16.8	3.7	1000	107.6
Substitute PG64-22	867.7	16.2	3.6	1000	111.4
Substitute PG64-22 +RAP/RAS as JMF	859.0	12.4	2.7	1000	99.3
Substitute PG64-22 +RAP/RAS as JMF +10%	1048.0	16.8	3.7	1000	118.5

Table 3.12. Overlay test results for District 2

Asphalt Mixture Material	Max Load, lb	Fracture area, lb-in	Fracture Energy, lb-in/in^2	Number of Cycles to Failure	Crack Resistance Index, β
Specified PG76-28	533.7	9.3	2.1	1000	100.9
Substitute PG70-28	575.1	9.5	2.1	1000	104.0
Substitute PG70-28 +RAP as JMF	543.7	9.2	2.0	1000	96.9
Substitute PG70-28 +RAP as JMF +10%	675.6	11.3	2.5	1000	104.4

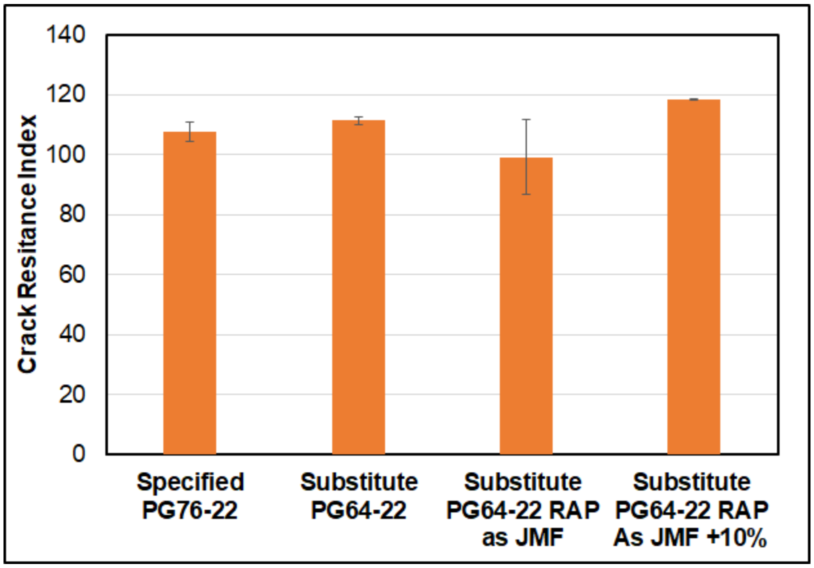

Figure 3.18. Crack resistance index results for District 1

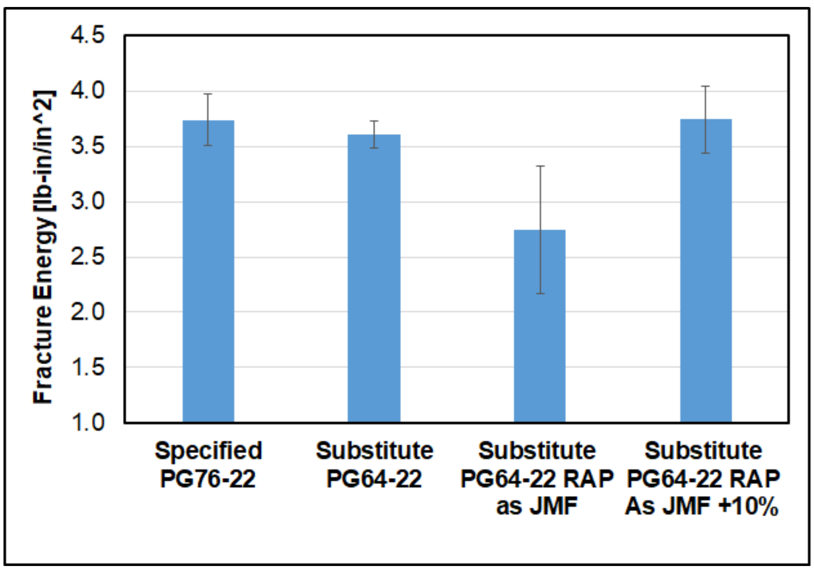

Figure 3.19. Fracture Energy results for District 1

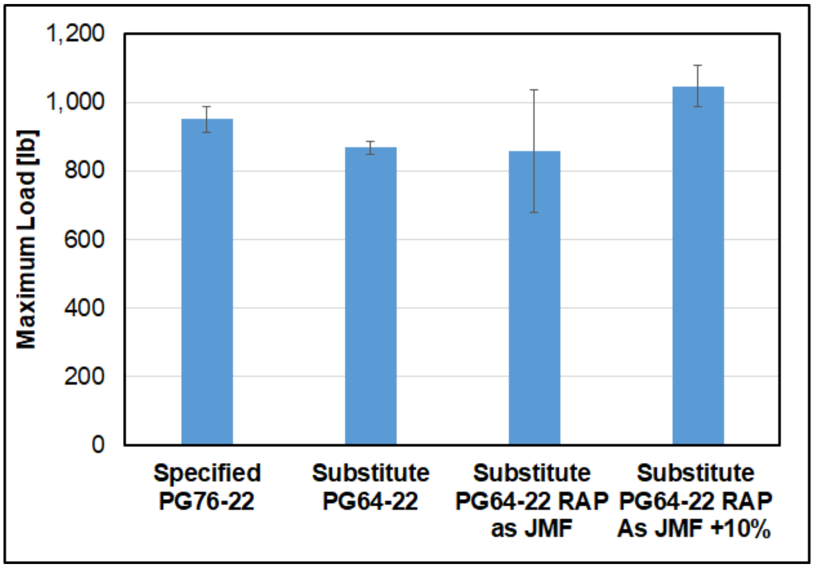

Figure 3.20. Maximum load for District 1

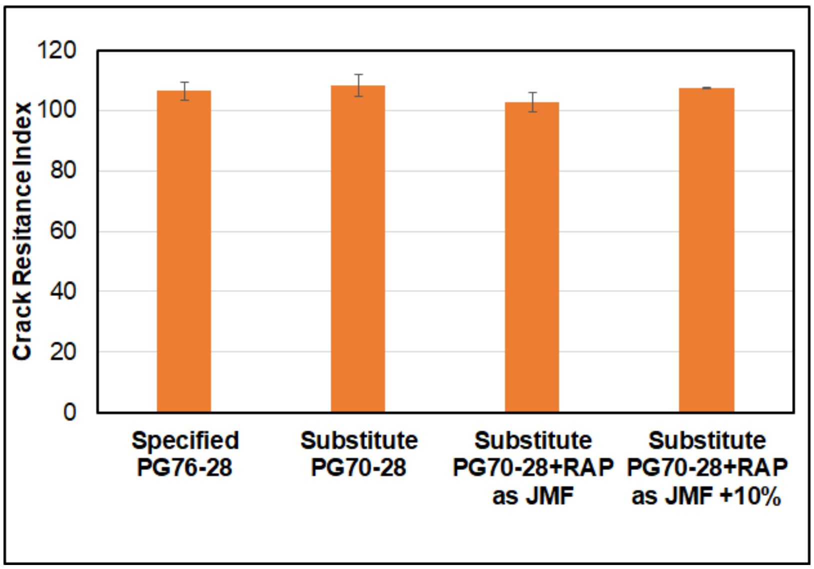

Figure 3.21. Crack resistance index results for District 2

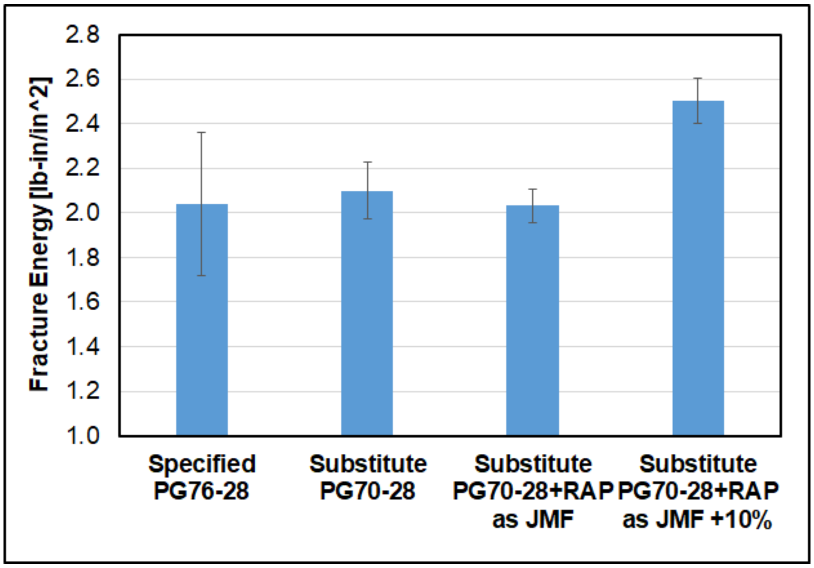

Figure 3.22. Fracture Energy results for District 2

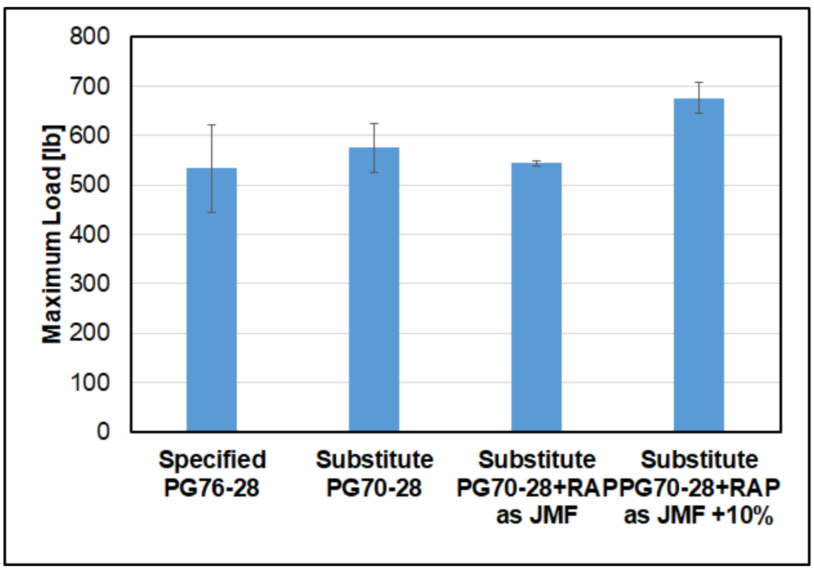

Figure 3.23. Maximum load for District 2

3.5 SUMMARY

This Chapter presented the results from the binder and mixture performance tests conducted using various combinations of materials from two different field sites. The following chapter presents a summary of important observations that can be drawn from these results.

CHAPTER 4. CONCLUSIONS AND SUMMARY

This study evaluated the expected performance of asphalt binders and mixtures with and without RAP and binder grade substitutes. For mixtures, the Hamburg Wheel tracking test and the Overlay Test were used to assess the rutting and cracking performance of mixtures. The following are some of the key observations that can be drawn for binders and mixtures from the many topics discussed in this study

4.1 BINDER EVALUATION

1. Adding recycled binder from RAP typically increase the high grade according to the PG system. This is expected due to the aged nature of the recycled material.

2. The percent recovery and non-recoverable creep compliance show mixed results due to the addition of recycled binder. It is possible that the recycled binder also contains polymer that may positively contribute (up to a limit) to the overall properties of the binder in the mix (virgin + recycle binder). However, this aspect must be studied more carefully in the future.

3. Glover-Rowe parameter and stiffness typically increase as recycled binder from RAP increases. Assuming that this indicator is a reflection of fatigue cracking resistance. It appears that fatigue cracking resistance decreases with addition of RAP. However, this change was small for one RAP and very significant for the other. This also suggests the need for more closely examining the binder quality in the RAP prior to allowing grade substitution.

4. The low temperature grade and the parameter ΔT_c typically increase as recycled binder from RAP is added. The m-value seems to be more effected by the inclusion of RAP compared to the stiffness.

4.2 MIXTURE EVALUATION

1. Inclusion of RAP show better or similar performance in the Hamburg Wheel Tracking test.

2. Fatigue testing do not show any consistent or significant trends from addition of RAP. Additional studies may be required to further evaluate this.

REFERENCES

AASHTO M302, M. (2008). Standard specification for superpave volumetric mix design. *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO M320, M. (2017). Standard specification for performance-graded asphalt binder. *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO MP2, M. (2001). Standard specification for superpave volumetric mix design. *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO TP101, T. (2014). Standard method of test for estimating damage tolerance of asphalt binders using the linear amplitude sweep. *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO TP2, T. (1999). Method for the quantitative extraction and recovery of asphalt binder from asphalt mixtures. *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO TP313, T. (2011). Determining the flexural creep stiffness of asphalt binder using the bending beam rheometer (bbr). *American Association of State Highway and Transportation Officials, Washington, DC*.

AASHTO TP70, T. (2009). Standard method of test for multiple stress creep recovery (mscr) test of asphalt binder using a dynamic shear rheometer (dsr). *American Association of State Highway and Transportation Officials, Washington, DC*.

Al-Qadi, I. L., Carpenter, S. H., Roberts, G., Ozer, H., Aurangzeb, Q., Elseifi, M., and Trepanier, J. (2009). Determination of usable residual asphalt binder in rap. Technical report, Illinois Center for Transportation (ICT).

Anderson, R. M., King, G. N., Hanson, D. I., and Blankenship, P. B. (2011). Evaluation of the relationship between asphalt binder properties and non-load related cracking. *Journal of the Association of Asphalt Paving Technologists*, 80.

ASTM D2872, D. (2012). Standard test method for effect of heat and air on a moving film of asphalt (rolling thin-film oven test). *USA: Annual Book of ASTM Standards*.

ASTM D6521, D. (2013). Standard practice for accelerated aging of asphalt binder using a pressurized aging vessel (pav). *USA: Annual Book of ASTM Standards*.

ASTM D7175, D. (2015). Standard test method for determining the rheological properties of asphalt binder using a dynamic shear rheometer. *USA: Annual Book of ASTM Standards*.

ASTM D7405, D. (2015). Standard test method for multiple stress creep and recovery (mscr) of asphalt binder using a dynamic shear rheometer. *USA: Annual Book of ASTM Standards*.

Bahia, H. U., Hanson, D., Zeng, M., Zhai, H., Khatri, M., and Anderson, R. (2001). *Characterization of modified asphalt binders in superpave mix design*. Number Project 9-10 FY'96.

Behnood, A. (2016). *Rheological properties of asphalt binders: An analysis of the Multiple Stress Creep Recovery test*. PhD thesis, Purdue University.

Bennert, T. (2012). Advanced characterization testing of rap mixtures designed and produced using a ârap binder contribution percentageâ. *Center for Advanced Infrastructure and Transportation, Rutgers University, Piscataway, NJ*.

Bukowski, J., Youtcheff, J., and Harman, T. (2011). The multiple stress creep recovery (mscr) procedure. *Federal Highway Administration*.

Bukowski, J. R. (1997). Guidelines for the design of superpave mixtures containing reclaimed asphalt pavement (rap). In *Memorandum, ETG Meeting, FHWA Superpave Mixtures Expert Task Group, San Antonio, TX*.

Copeland, A. (2011). Reclaimed Asphalt Pavement in Asphalt Mixtures : State of the Practice (No. FHWA-HRT-11-021). (april).

D'Angelo, J. (2007). Effect of polymer-asphalt binder compatibility and cross-link density of non-recoverable compliance in the mscr test method. *Southeast Asphalt User/Producer Group, San Antonio, Tex*.

Daniel, J. and Lachance, A. (2005). Mechanistic and volumetric properties of asphalt mixtures with recycled asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, (1929):28–36.

Daniel, J. S. and Mogawer, W. S. (2010). Determining the effective pg grade of binder in rap mixes. Technical report.

DuBois, E., Mehta, Y., and Nolan, A. (2014). Correlation between multiple stress creep recovery (mscr) results and polymer modification of binder. *Construction and Building Materials*, 65:184–190.

DâAngelo, J. (2010). New high-temperature binder specification using multistress creep and recovery. *Transportation Research Circular, n. E-C147*, pages 1–13.

Glover, C. J., Davison, R. R., Domke, C. H., Ruan, Y., Juristyarini, P., Knorr, D. B., and Jung, S. H. (2005). Development of a new method for assessing asphalt binder durability with field validation. *Texas Dept Transport*, 1872.

Guo, M., Motamed, A., Tan, Y., and Bhasin, A. (2016). Investigating the interaction between asphalt binder and fresh and simulated rap aggregate. *Materials & Design*, 105:25–33.

Hintz, C. (2012). *Understanding mechanisms leading to asphalt binder fatigue*. PhD thesis, The University of Wisconsin-Madison.

Hintz, C. and Bahia, H. (2013). Simplification of linear amplitude sweep test and specification parameter. *Transportation Research Record: Journal of the Transportation Research Board*, (2370):10–16.

Hintz, C., Velasquez, R., Johnson, C., and Bahia, H. (2011). Modification and validation of linear amplitude sweep test for binder fatigue specification. *Transportation Research Record: Journal of the Transportation Research Board*, (2207):99–106.

Huang, B., Li, G., Vukosavljevic, D., Shu, X., and Egan, B. (2005). Laboratory investigation of mixing hot-mix asphalt with reclaimed asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, (1929):37–45.

Johnson, C. M. (2010). *Estimating asphalt binder fatigue resistance using an accelerated test method*. PhD thesis, University of Wisconsin–Madison.

Kandhal, P. S. and Foo, K. Y. (1997). Designing recycled hot mix asphalt mixtures using superpave technology. In *Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation*. ASTM International.

Kandhal, P. S., Rao, S. S., Watson, D. E., Young, B., et al. (1995). Performance of recycled hot mix asphalt mixtures. *Auburn: National Center for Asphalt Technology*, 7(1):28–45.

Li, X., Marasteanu, M., Williams, R., and Clyne, T. (2008). Effect of reclaimed asphalt pavement (proportion and type) and binder grade on asphalt mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, (2051):90–97.

Little, D. and Epps, J. A. (1980). Evaluation of certain structural characteristics of recycled pavement materials. In *Proceedings of the Association of Asphalt Paving Technologists*, volume 49, pages 219–251.

McDaniel, R. S., Soleymani, H., Anderson, R. M., Turner, P., and Peterson, R. (2000). Recommended use of reclaimed asphalt pavement in the superpave mix design method. *NCHRP Web document*, 30.

Nösler, I., Tanghe, T., and Soenen, H. (2008). Evaluation of binder recovery methods and the influence on the propertiesof polymer modified bitumen. In *Proceedings of the 4th Eurasphalt and Eurobitume Congress, Copenhagen, Denmark*.

Roque, R., Yan, Y., Cocconcelli, C., and Lopp, G. (2015). *Perform an investigation of the effects of increased reclaimed asphalt pavement (RAP) levels in dense graded friction courses*. University of Florida, Department of Civil and Coastal Engineering.

Rowe, G., King, G., and Anderson, M. (2014). The influence of binder rheology on the cracking of asphalt mixes in airport and highway projects. *Journal of Testing and Evaluation*, 42(5):1063–1072.

Rowe, G. and Sharrock, M. (2011). Alternate shift factor relationship for describing temperature dependency of viscoelastic behavior of asphalt materials. *Transportation Research Record: Journal of the Transportation Research Board*, (2207):125–135.

Safaei, F., Lee, J.-s., Nascimento, L. A. H. d., Hintz, C., and Kim, Y. R. (2014). Implications of warm-mix asphalt on long-term oxidative ageing and fatigue performance of asphalt binders and mixtures. *Road Materials and Pavement Design*, 15(sup1):45–61.

Santucci, L. (2007). Recycling asphalt pavements: A strategy revisited. *Tech Topics*, (8).

Servas, V. (1982). Hot mix recycling. *Ann. Transportation Conv,*, 3.

Shah, A., McDaniel, R., Huber, G., and Gallivan, V. (2007). Investigation of properties of plant-produced reclaimed asphalt pavement mixtures. *Transportation Research Record: Journal of the Transportation Research Board*, (1998):103–111.

Shirodkar, P., Mehta, Y., Nolan, A., Sonpal, K., Norton, A., Tomlinson, C., Dubois, E., Sullivan, P., and Sauber, R. (2011). A study to determine the degree of partial blending of reclaimed asphalt pavement (rap) binder for high rap hot mix asphalt. *Construction and Building Materials*, 25(1):150–155.

Tex-241-F, F. (2015). Compacting bituminous specimens using the superpave gyratory compactor (sgc). *Texas Department of Transportation (TxDOT), Construction Division*.

Tex-242-F, F. (2014). Hamburg wheel-tracking test. *Texas Department of Transportation (TxDOT), Construction Division*.

Tex-248-F, F. (2017). Overlay test. *Texas Department of Transportation (TxDOT), Construction Division*.

Tran, B. and Hassan, R. (2011). Performance of hot-mix asphalt containing recycled asphalt pavement. *Transportation Research Record: Journal of the Transportation Research Board*, (2205):121–129.

TxDOT (2014). Standard specifications for construction and maintenance of highways,streets, and bridges. *Austin, TX.*

Wang, C., Castorena, C., Zhang, J., and Richard Kim, Y. (2015). Unified failure criterion for asphalt binder under cyclic fatigue loading. *Road Materials and Pavement Design*, 16(sup2):125–148.

West, R. (2010). Reclaimed asphalt pavement management: best practices. *Auburn, AL: National Center for Asphalt Technology, NCAT Draft Report*.

Zhou, F., Li, H., Chen, P., Scullion, T., et al. (2014). *Laboratory Evaluation of Asphalt Binder Rutting, Fracture, and Adhesion Tests*. Texas A & M Transportation Institute.